IMPACT OF SOIL EROSION ON CROP YIELDS IN NORTH AMERICA

Christoffel den Biggelaar,[1] Rattan Lal,[1] Keith Wiebe,[2] and Vince Breneman[2]

[1]School of Natural Resources,
Ohio State University,
Columbus, Ohio 43210

[2]USDA Economic Research Service,
Washington, DC 20036

I. INTRODUCTION

Several reviews and research summaries have been published in the past on the relation between soil erosion and productivity (Stallings, 1957; National

Advances in Agronomy, Volume 72

0065-2113/01 $35.00

Agricultural Lands Study, 1981; NSE-SPRPC, 1981; Langdale and Shrader, 1982; Crosson and Stout, 1983; Anderson and Gregorich, 1984; Burnett *et al.*, 1985; Larson *et al.*, 1985; Mannering *et al.*, 1985; Nowak *et al.*, 1985; Renard and Follett, 1985; Maetzold and Alt, 1986; Heimlich, 1989; Lal, 1987, 1988, 1998; Pierce, 1991; Cann *et al.*, 1992). The topic has also been the subject of a number of conferences and workshops (Rijsberman and Wolman, 1984; ASAE, 1985; Larson *et al.*, 1990). In several of these reviews, the authors provided global or national estimates of the long-term decrease in productivity as a result of accelerated erosion, with little attention to spatial variations resulting from soil and climatic differences.

In this chapter, we use spatially referenced data to link study sites with soil orders and erosion rates to estimate the productivity losses in each soil order. This information is then used to estimate the production and economic losses due to soil erosion for four crops that have been the subject of most erosion–productivity studies in North America: maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), soybeans [*Glycine max* (L.) Merr.], and cotton (*Gossypium spp.* L.). A number of studies have investigated productivity effects of erosion on other crops, but they are too few in number, too old, or too narrowly focused on locally significant crops to make useful estimates. These are discussed under “Hay and Fodder Crops” and “Miscellaneous Crops”. Soil loss is used as an indicator of erosion. In accord with most of the studies reviewed, topsoil depth (TSD) is used as the independent variable.

II. BACKGROUND

Human activities both influence the structure, fertility, and composition of soils and are influenced by the properties and availability of soils (Davis and Browne, 1996). The relationship between humans and soils is characteristic of the ways through which humans interact with the environment, responding to potentials, recognizing limits, and adapting the environment to suit human needs (Harris and Warkentin, 1974). Human activities have, in turn, changed soil fertility or eliminated the need for soils for crop production altogether. However, although some high-value specialty crops are today grown in soil-less artificial media in greenhouses [notably tomatoes (*Lycopersicon esculentum* Mill.), cucumbers (*Cucumis sativus* L.), lettuce (*Lactuca sativa* L.) and flowers], soil-based agriculture continues to be the most important form of food and fiber production. Soil provides nutrients, water, and support to plants as well as is host to innumerable macro- and microorganisms both beneficial and harmful to crops.

Soil conservation and management are important so that soils can continue to provide these services into the future. In many parts of the world, however, soil conservation and management leave much to be desired, resulting in the degradation of the soil resource leading to a decrease in its productive potential. Johnson and Lewis (1995) found that there is general agreement in the literature concerning two critical aspects of soil degradation. First, soil degradation involves a substantial decrease in the biological productivity of a soil system and, second, this decrease is the result of processes resulting from human activities rather than natural events. Based on these criteria, we define soil degradation as the substantial decrease in a soil's biological productivity or usefulness due to human interference, assuming other factors such as technology, management, and weather remain constant (Bojö, 1996).

Productivity is a measure of the rate of accumulation of energy. Productivity can be defined and measured in many ways, such as output per unit of land, output per unit of labor, or output per unit of other input(s) used. In the context of soil productivity, it is the productive potential of the soil system that allows the accumulation of energy in the form of vegetation (Stocking, 1984). Production is the total accumulation of energy, irrespective of how quickly, over what area, or with what assistance it accumulates. Yield, or output per unit area over a given time period, is a measure of production, which can be used as an indicator (albeit an imperfect one) of productivity. Yields are an expression of historical production, whereas productivity is a measure of potential (future) productivity (Tengberg and Stocking, 1997). Production (total biomass) can remain constant or even increase as the soil becomes degraded (Dregne, 1995). Stocking (1994) observed that crop yields may increase even though degradation may reduce long-term soil productivity, causing a loss to future economic returns to production. Johnson and Lewis (1995) therefore added usefulness as a crucial attribute of soil degradation. For example, as a result of degradation, species composition changes resulting in poorer quality biomass may make it less useful to people, although total biomass production may not be affected. A similar observation was made by Young *et al.* (1985).

A. Effects of Soil Degradation

Soils are a finite resource created and degraded through both natural and human-induced processes. Soils are formed in a slow, continuous, and gradual process involving the breakdown of minerals during biological, physical, and chemical processes (National Agricultural Lands Study, 1981). Scientists estimate that 2.5 cm (1 in.) of new topsoil is formed every 100 to 1000 years (Pimentel *et al.*, 1976), which is equivalent to a rate of 0.4–4.0 Mg ha^{-1} yr^{-1}. The rate varies widely, influenced by land use, climate, vegetation, soil disturbances, and the nature of the land (Brady and Weil, 1999). Human activities can either aggravate or mitigate soil degradation. Mostly, though, human activities accelerate the natural degradative processes, so that the rate of soil formation is greatly outweighed by soil loss as a result of degradation. While there is widespread evidence that soil losses resulting from erosion far exceed the natural rate of soil formation, the impact of such losses on crop yields or production has not been well established in physical or economic terms, although there have been many attempts to do so (van Baren and Oldeman, 1998).

The effects of degradation on soil resources can be grouped into two categories: those that are reversible (e.g., nutrient levels, pH, organic matter, and biological activity) and those that are irreversible *given present technological and economic resources* (e.g., rooting depth, water holding capacity, structure, and texture). The reversibility or irreversibility of a specific type of soil degradation depends not only on available technology, but also in most cases on economic costs and returns. For example, irrigation can mitigate a decline in water-holding capacity, but may not be economically viable in all circumstances.

Results from field studies and simulation models indicate that there is a large variation in the way soil degradation affects its quality (Maetzold and Alt, 1986). Some soils experience consistent productivity reductions with degradation, while others suffer no loss until some critical point in one (or more) yield-determining factor(s) is reached, at which time significant yield losses occur with further degradation (Hoag, 1998). The effects of degradation may also vary from year to year, so that long-term degradative effects are not easily apparent. For example, eroded soils with reduced plant-available water-holding capacities and/or infiltration rates often show greater yield losses in drought years compared with uneroded soils (Shaffer, 1985; Swan *et al.*, 1987). During years with normal or above-average rainfall, however, yields on eroded and uneroded soils may be identical. Irrigation can reduce yield differences even in drought years, but involves an economic cost. While yield differentials can be masked by the use of irrigation, other degradative processes may continue unabated (e.g., loss of organic matter and soil structure) or new ones may be introduced (e.g., alkalinization and salinization).

Although there are many forms of soil degradation (e.g., physical, chemical, and biological), in this chapter we focus solely on erosion, which is a form of physical degradation. Erosion is chosen as it is widespread, frequently studied, and the most visible form of soil degradation. Globally, Oldeman *et al.* (1990) estimated that 85% of soil degradation is due to erosion. Erosion is a natural process that has occurred for as long as the earth has been in existence (Larson *et al.*, 1983a). Some of the most productive soils in the world (e.g., loess and alluvial soils) are a result of erosional processes. Thus, not all erosion can be classified as degradation. As discussed above, soil degradation results from the acceleration, by humans, of naturally occurring processes (Davis and Browne, 1996). Although a popular notion, fueled by some authors (Brown, 1994; Brown and Wolf, 1984a, 1984b; Ehrlich and Ehrlich, 1991), states that erosion is more severe than ever before and poses severe threats to the long-run productivity of agriculture in the United States (Cleveland, 1995) and Canada (Fairbairn, 1984; Prairie Farm Rehabilitation Agency, 1983; Sparrow, 1984), Larson *et al.* (1983a) argued that there is insufficient evidence available to support or refute that notion.

Research by agronomists, agricultural engineers, soil scientists, and agroecologists have identified the following effects of soil erosion (Follett and Stewart, 1985; Lal and Stewart, 1990; Pimentel, 1993; Cleveland, 1995; Loch and Silburn, 1997): (i) reduction in soil depth and potential rooting depth; (ii) reduction in soil organic matter content; (iii) reduction in nutrient availability; (iv) nonuniform removal of topsoil within a field; (v) exposure of, and/or mixing of topsoil with, subsoil of poorer physical, biological, and chemical properties; (vi) changes in soil physical properties (such as changes in bulk density, water infiltration, water-holding capacity, texture, or structure); or (vii) some combination of the above factors.

These changes in the physical, chemical, and biological qualities of soil are often the primary reason for monitoring soil erosion, as they affect soil productivity. Productivity can reflect soil erosion if yields decline with progressive erosion or if input use increases to compensate for declines in soil quality due to erosion (ERS, 1997). However, soils of poor physical quality (as measured by erosion and changes in texture and organic matter) can sometimes produce very high yields without large increases in input use (Vesterby and Krupa, 1993).

Because of the emphasis on a soil's capacity to produce plants or biomass (see Section II), productivity is usually expressed in terms of crop yield or output per unit area over a given time period (NSE-SPRPC, 1981). Yield data are the way that farmers, policy makers, and the public typically consider agricultural production data, and they are also a basic measure of productivity in agricultural experiments (Tomlin and Umphrey, 1996). Crop yields are, therefore, used as the measure of productivity in this review.

B. Factors Affecting Crop Yields

While soil provides the basis for agricultural production, it is by no means the only determinant of crop yields. For example, Butell and Naive (1978) identified weather, fertilizer use, technology, and planted area as the major factors affecting corn yields. In the period of 1954–1977, corn yields in the United States increased from 2.5 to 5.6 Mg ha^{-1}. According to these authors, the higher rate of fertilizer use since the mid-1950s accounted for over half the increase in corn yields, while technology (better management and cultural practices facilitated by improved varieties of corn and advances in pesticides, mechanization, and irrigation) accounted for the rest of the increase. In general, crop yields are a function of interacting factors including soil characteristics (S), management practices used (M), pest and disease incidence (PD), and climatic conditions before and during the respective growing season (C). Crop yield, therefore, can be represented by the following function:

$$\text{Yield} = f(\text{S, C, M, PD}).$$

There is a feedback mechanism between crop yields and soils (Lindert, 1999) which may be positive (e.g., the addition of organic matter from stubble and plant residues and, for N-fixing crops, the addition of nitrogen) or negative (e.g., the removal of nutrients through harvests and loss of soil structure associated with root crops, particularly during harvest operations in wet conditions). Similarly, Young *et al.* (1985, quoted by Cleveland, 1995) observed that yield-enhancing technological change may not actually offset erosion damage, but may in fact intensify productivity damage from erosion.

Each of the factors in the above production function consists of a number of subfactors that may influence crop production and yield levels (Fig. 1). The question of long-term effects of erosion on crop productivity is, therefore, a complex one due to the many interactive factors that affect plant growth and yield (Frye, 1987). Evaluation of the relationship between soil erosion and productivity is complicated also by the effects of an ever-increasing level of technology on crop production. To determine the effect of a single soil factor (erosion) on yield (as the indicator of soil productivity) therefore requires that all other factors determining yield be kept constant or controlled as much as possible.

C. Effects of Soil Erosion on Crop Yields

Soil erosion affects crop production and yields in multiple ways. Physical loss of soil through erosion, leading to a decline in TSD, is the most visible form of degradation; its effect is both long-term and cumulative. Critics of the concept of soil loss note that nearly 75% of the "eroded" (detached and transported) soil is eventually deposited on another site and thus is not truly "lost," as it moves from one part of the landscape to another (Larson *et al.*, 1983a; National Agricultural Lands Study, 1981; Office of Technology Assessment, 1982). It is the nutrient-rich organic and clay particles that tend to be the soil particles dislodged and carried away by erosion. This loss of soil organic matter (SOM), nutrients, and water-holding capacity causes significant qualitative changes in soils (National Agricultural Lands Study, 1981) (see Section II,A). Therefore, it may not be the decrease in depth of topsoil or solum or to a root-restrictive layer *per se* that impacts yields, but rather the changes the loss of soil brings about in other soil factors, such as nutrient levels, pH, water-holding capacity, texture, infiltration rates, and SOM over time, possibly rendering agriculture unprofitable or even impossible. For example, changes in soil texture and tilth due to erosion may necessitate heavier machinery to work the soil or more passes to prepare a suitable seed bed, increasing the risk of compaction and the formation of plow and traffic pans (Frye, 1987). This can cause delays in planting in spring as the soils remain too cold and wet to enable seedbed preparation and planting. Other effects of erosion include losses of crop stand and loss of arable land area to gully formation and land slides and

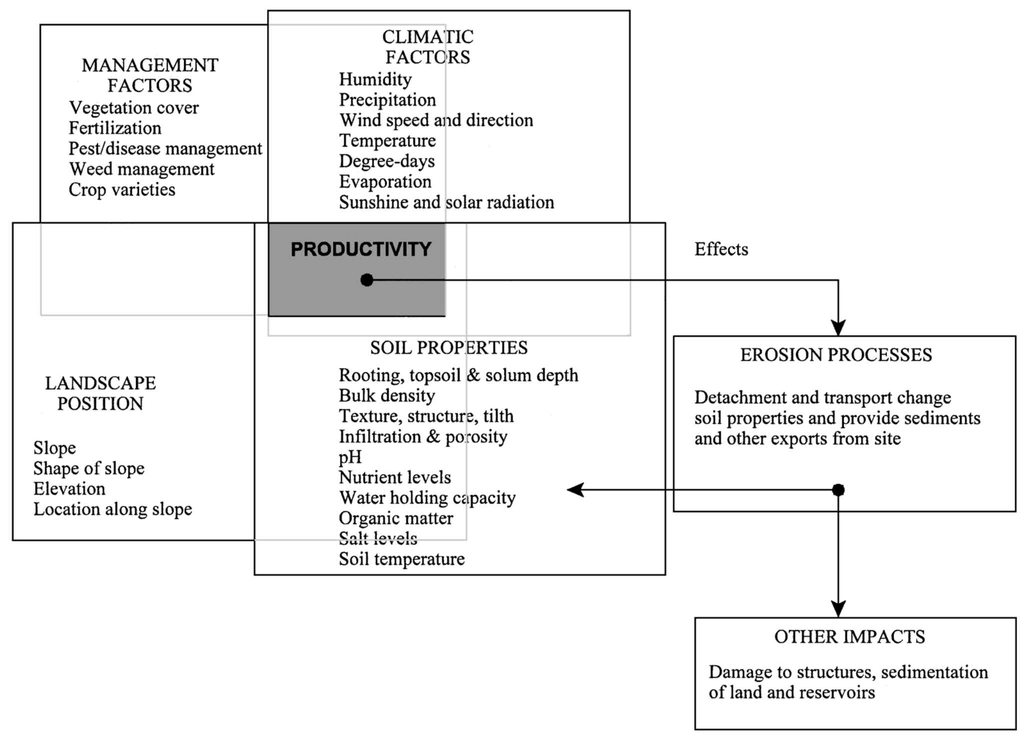

Figure 1 Factors affecting crop yield and productivity. (Adapted from S. J. Perrens and N. A. Trustrum, 1984. Assessment and Evaluation of Soil Conservation Policy–Report Workshop on Policies for Soil and Water Conservation, 25–27 January 1983, East West Center, Honolulu, Hawaii).

crop burial by sediment deposition (Lal, 1987). However, even if soils become less productive for one crop, they may remain highly productive for others better able to exploit adverse or resource-limiting conditions.

Although erosion is the most frequently studied type of degradation affecting crop yields, the precise relationship between erosion and productivity remains unclear and difficult to quantify (Littleboy *et al.,* 1996; Stocking and Sanders, 1993). Erosion and productivity are also not independent; both are influenced by other factors (Ponzi, 1993). Moreover, the loss in productivity set in motion by accelerated erosion may be a self-sustaining process: Loss of production on eroded soil may further degrade its productivity (through loss of crop cover, poor stands, and reduced amount of residues returned to the soil) which, in turn, may accelerate erosion (Ponzi, 1993).

In a majority of studies that aimed at quantifying the relationship between soil erosion and productivity, yield declines were related to a loss in TSD. Hoag (1998), however, concluded that “TSD is not generally an adequate measure of productivity. The most profitable management of a soil will depend on the quality and distribution of soil layers in the overall rooting zone. Soil substitution and mixing, as well as depth, can affect productivity. Because soil layers are not uniform, productivity may even increase or be unaffected by erosion.”

In addition to the on-site effects of erosion on soil quality, the export of soil, nutrients, and pesticides may have adverse off-site effects through siltation of streams and reservoirs and damage to water quality (Loch and Silburn, 1997). This chapter does not address the off-site effects and costs of erosion.

III. DATA SOURCES AND ANALYSES

A. Data Sources

This chapter is limited to studies based on field research on soil erosion–productivity in the United States and Canada that reported quantitative yield results (e.g., bushels per acre, tons per acre, or megagrams or kilograms per hectare). Studies which reported results only as a percentage decline in yield were excluded. Also excluded were studies based on simulation models or regression analysis, unless they included data from field studies that were used to develop or test the models. Based on concerns articulated by Boardman (1998) about the “misinterpretation and uncritical use of original field data“ in studies using secondary data, this analysis is based on original studies.

Information on the area of soil orders in the United States was obtained from NRCS’s Soil Survey Staff (1999), while that for Canada was inferred from data of the global soil regions map by NRCS’s World Soil Resources Staff (1997). Information on the extent of erosion and the amount of cultivated cropland by soil order in the United States was obtained from the 1997 National Resources Inventory (NRCS, 1999). Crop yield data were obtained from the 1987, 1992, and 1997 Censuses of Agriculture (United States Bureau of the Census 1987, 1993; NASS, 1999). Data on cultivated cropland and crop yields for Canada were obtained from the 1996 census of agriculture (Statistics Canada, 1997) and Internet sites of provincial departments of agriculture. Data on the extent of soil erosion in Canada were obtained from Dumanski *et al.* (1994) and Agriculture and Agri-Food Canada (1998).

B. Data Analysis and Interpretation

An Access database was developed to enter the information from the studies identified in the literature. As several studies comprised and reported on experimental results from more than one soil series, a separate record was created for each at the soil subgroup level. Soil series information was translated into the soil subgroup of the U.S. Soil Taxonomy using the USDA–NRCS Soil Survey Division's Official Soil Series Descriptions on the Internet. Canadian soils are classified using a different taxonomy; soil series were reclassified according to the U.S. Soil Taxonomy at the soil order level (e.g., Chernozems as Mollisols, Luvisols as Alfisols, and Podzols as Spodosols). Latitude and longitude information for the location of the experiments, if not provided in the articles, was obtained from the USGS (2000) Geographic Names database for locations in the United States, and from the Natural Resources Canada (1995) Geographic Names of Canada database for that country.

The yields reported in the literature were used to calculate mean decreases in yield per centimeter or metric ton of soil loss due to erosion. For ease of calculation and comparison of the various studies, we assumed linear yield declines even though in most cases observed yield declines were not linear. For studies using topsoil removal/addition and TSD as experimental methods, actual TSD values were used. To calculate yield impact per centimeter of soil loss in studies using soil phases as the experimental method, we assumed a difference of 7.5 cm between severely and moderately and between moderately and slightly eroded phases and a difference of 10 cm between slightly eroded and depositional phases (Soil Survey Staff, 1999). Standard conversion factors employed for the U.S. Census of Agriculture (NASS, 1999) were used for weights, measures, and yields of various commodities.

Yield declines have generally been calculated using uneroded or slightly eroded phases as a reference, which may not be representative of farmers' conditions that consist of a range of soil depths. We therefore used the mean yields across all experimental plots as the "standard" reference yield. It would be more correct to use the mean yield for the various crops obtained under farmer management for the areas where the experiments were implemented, but such information is not available in the desired format (i.e., disaggregated by county, year, and soil order or subgroup).

Technological advances have enabled an increase in crop yields over time in spite of accelerated erosion. The impact of these advances is masked by averaging yields and yield impacts of soil loss over all experimental plots, soil series/subgroups, climate regions, experimental duration, and management practices. To account for the effect of technological advances on crop yield and yield loss due to erosion, we compared studies on maize carried out prior to and after 1960 by soil order and experimental method. For other crops, this comparison was not possible as there were too few studies in either one or the other time period. A decal comparison would be more desirable to assess the effect of technological advances, but there are too few soil erosion–productivity studies, even in North America, to conduct such an analysis.

To estimate the annual amount of production loss due to erosion, we used four types of data: (1) the area of maize, wheat, soybeans, and cotton by soil order; (2) the mean annual erosion rates for various soil orders; (3) average crop yields obtained by farmers on those soils; and (4) average yield impacts calculated from the review of soil erosion–soil productivity studies. Crop areas by soil order were calculated from the 1997 NRI for the United States and from the Canadian Census of Agriculture for Canada. Average erosion rates by soil order were obtained from an overlay of the soil order map and the 1992 mean annual erosion rates on crop and CRP land for the United States and from Dumanski *et al.* (1994) and Agriculture and Agri-Food Canada (1998) for Canada. Crop yield data are averages of yields reported in the 1987, 1992, and 1997 Censuses of Agriculture for the United States and averages of the last 5 years of available data for Canada. The mean yield declines used for the calculations are average mean yield declines for the respective crops and soil orders across experimental methods. For ease of calculation, we assumed that erosion causes a uniform soil removal across the field.

For the estimation of economic impact, we multiplied the annual production loss estimates by the 2000 crop prices from the USDA Agricultural Baseline Projections to 2008 (USDA, 1999). The same prices were used for the calculations of economic impact of soil erosion in the United States and Canada assuming that farm prices are similar in both countries. Total annual production losses were divided by the crop area in each soil order to determine productivity losses on a per-hectare basis. The resulting figure was then multiplied by the same prices as used to calculate the overall economic impact to obtain the economic impact per hectare.

C. Location of Erosion–Productivity Studies

From a review of the literature, 90 field-based studies on soil erosion and productivity were identified. The database resulted in a total of 197 separate records, covering 75 soil subgroups—59 in the United States and 16 in Canada. The studies are not evenly dispersed over the territory of these countries, however. Rather, soil erosion–productivity studies are concentrated in a few areas: the corn belt in the Midwest and the Palouse area in the Pacific Northwest in the United States and Alberta in Canada. Figure 2 shows the locations of the various experiments in relation to soil orders. Looking at the study locations on the map of average annual erosion rates shown in Fig. 3 shows that most studies were not done in areas with the highest erosion rates. For example, only one study was located in eastern Colorado, although most of the cropland in that part of the state erodes at a rate of 18 Mg ha^{-1} yr^{-1} or more (based on 1992 NRI data). The studies in Texas were also not done in the areas experiencing the most severe erosion in the state. On the other hand, many of the studies in Illinois, Indiana, New York, North Dakota, and Ohio were located on land eroding at a rate of $<$4 Mg ha^{-1} yr^{-1}.

Mollisols and Alfisols are the most frequently studied soils in both the United States and Canada (Fig. 2 and Table I), reflecting the importance of these soils for the production of maize, soybeans, wheat and barley.

In the United States, a diversity of crops grown are on each soil type. Maize, however, was the most common crop in the experiments on Alfisols, Mollisols, and Ultisols. Wheat studies were primarily conducted on Mollisols, whereas the impact on soybean yield has been tested on many soils but mostly on Alfisols. In the Canadian studies, maize was the dominant crop in experiments on Alfisols, whereas wheat was the dominant test crop on Mollisols.

The use of erosion phases was the most commonly used method to determine the effect of erosion on yield. This method was used in 41% of the cases, followed

Table I

Soil Orders Represented in the Database (Number and Percentage of Records)

	United States		Canada	
Soil order	No. (%) of records	No. of soil subgroups represented	No. (%) of records	No. of soil subgroups represented
Alfisols	54 (35%)	17	17 (41%)	6
Mollisols	69 (45%)	24	24 (57%)	9
Ultisols	22 (14%)	7	n.d.[a]	n.d.
Aridisols	1 (0.7%)	1	n.d.	n.d.
Entisols	2 (1.3%)	2	n.d.	n.d.
Inceptisols	4 (2.6%)	4	n.d.	n.d.
Oxisols	1 (0.7%)	1	n.d.	n.d.
Spodosols	1 (0.7%)	1	1 (2%)	1
Total	155 (100%)		42 (100%)	

[a] n.d. = no data.

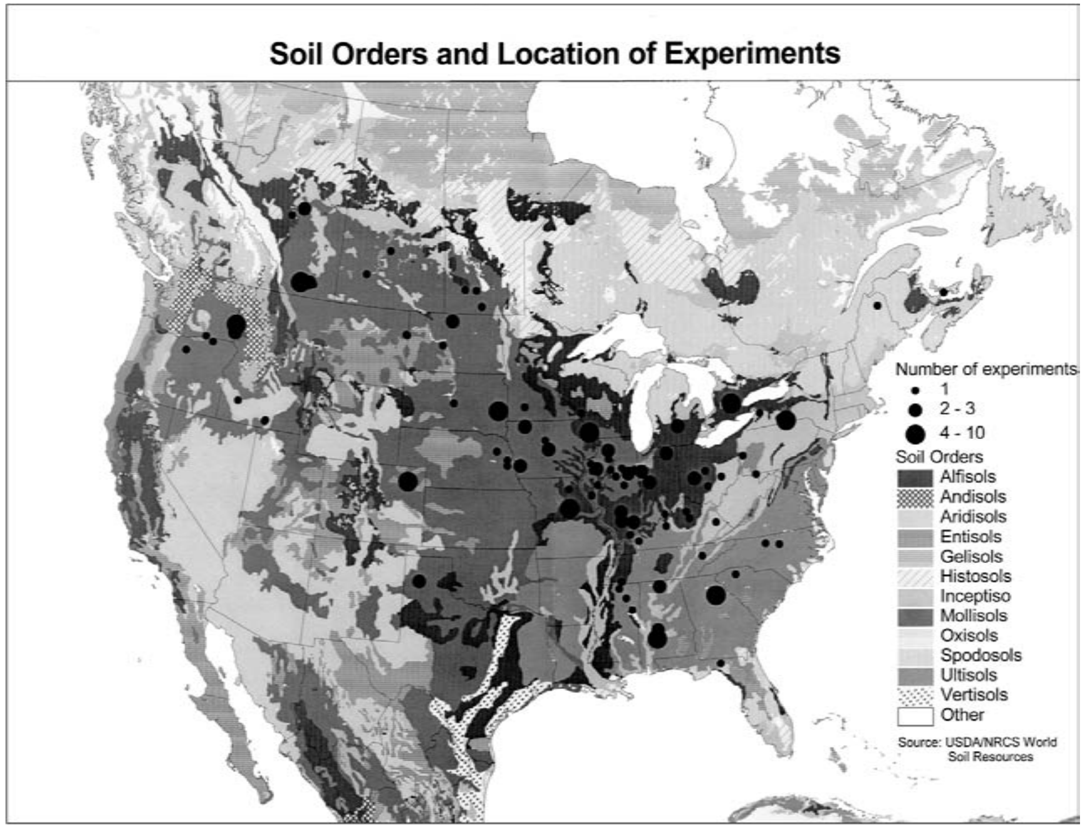

Figure 2 Soil order map of North America showing the location of the soil erosion-productivity experiments included in this chapter.

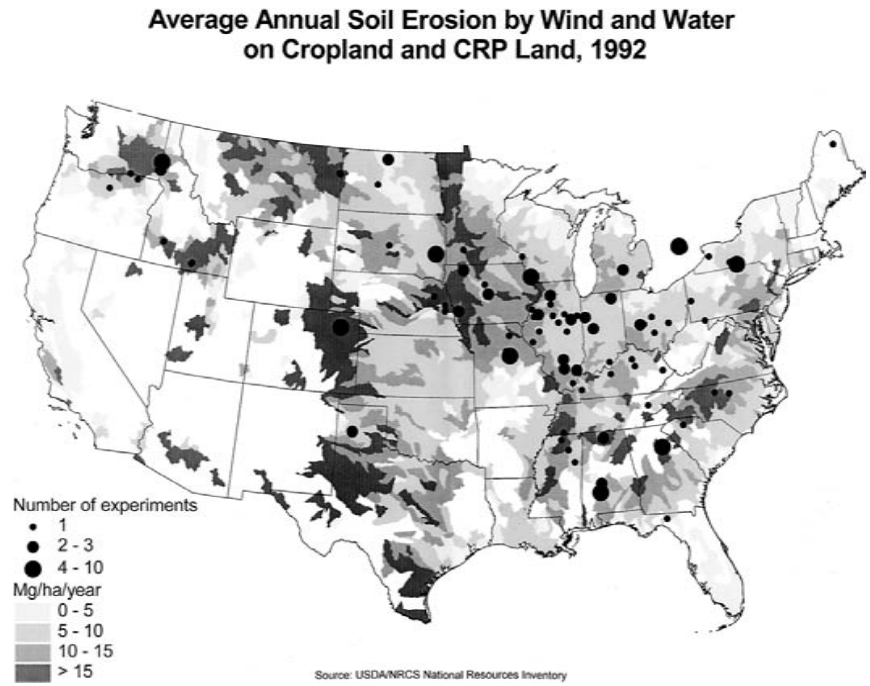

Figure 3 Average annual water and wind erosion on cropland and CRP land in 1992 in relation to the study sites (source: 1992 NRI).

by topsoil removal and addition (27%), TSD (22%), and depth to fragipan (7%). Soil surveys were used in one study, whereas management practices were used in six studies.

IV. RESULTS

A. Extent of Erosion in North America

Concerns about the severity of soil erosion in the United States date to the 1930s, when Bennett (1931) warned that millions of hectares of agricultural land had been "devastated" by erosion (Cleveland, 1995). The rate of erosion on U.S. cropland has declined in recent years due to conservation tillage and other measures encouraged by the 1985 farm bill and the removal from production of the most highly erodible cropland under the Conservation Reserve Program (CRP) (Magleby *et al.*, 1995). According to 1997 NRI data, the mean annual erosion rate on nonfederal cultivated cropland in the United States has declined from 17.9 Mg ha^{-1} in 1982 to 16.8 Mg ha^{-1} in 1987, 13.9 Mg ha^{-1} in 1992, and 12.5 Mg ha^{-1} in 1997 (NRCS, 1999). These trends correspond to a decline in soil erosion in the United States from 2.8 billion Mg yr^{-1} to 1.72 billion Mg yr^{-1} between 1982 and 1997. In 1992, seven states exceeded their 1982 erosion rates (i.e., Arizona, Connecticut, Minnesota, New Mexico, Utah, Washington, and Wyoming); in 1997, only Arizona and Connecticut remained above 1982 erosion rates (Fig. 4). Figure 4 also shows the erosion rate of cultivated cropland for Canada by province in 1997. Erosion rates are relatively high in Ontario and New Brunswick (10–15 Mg ha^{-1}), but rates in the prairie provinces are comparable to those in adjacent U.S. states.

Political units are not a particularly useful way to show erosion rates, as they may contain numerous soils differentially affected by erosion and vary in the amount of land in cultivation. The map in Fig. 3 shows the average annual soil erosion on cropland and CRP land in 1992. Comparing the maps in Figs. 3 and 4 reveals that the high erosion rates, for example, in Arizona, Utah, and Nevada are due largely to relatively small cultivated areas eroding at very high rates.

To estimate the loss of production due to erosion, we need to know the amount of cropland and cropland erosion rates for predominant soil orders. The data in Table II show average erosion rates by soil order. Erosion rates are highest on cropland on Aridisols (i.e., $>$25 Mg ha^{-1}). On soils that are most important to crop production in the United States (i.e., Alfisols, Mollisols, and Ultisols), average erosion rates are lower (11.5, 11.5, and 9.8 Mg ha^{-1} yr^{-1}, respectively) and are at or below the tolerable rate (*T*) established by NRCS. Assuming a bulk density of 1.5 Mg m^{-3}, the erosion rates on these soil orders translate into a soil loss of 0.65 to 0.76 mm yr^{-1} (Table II). Although *T* values vary by soil series and can be as

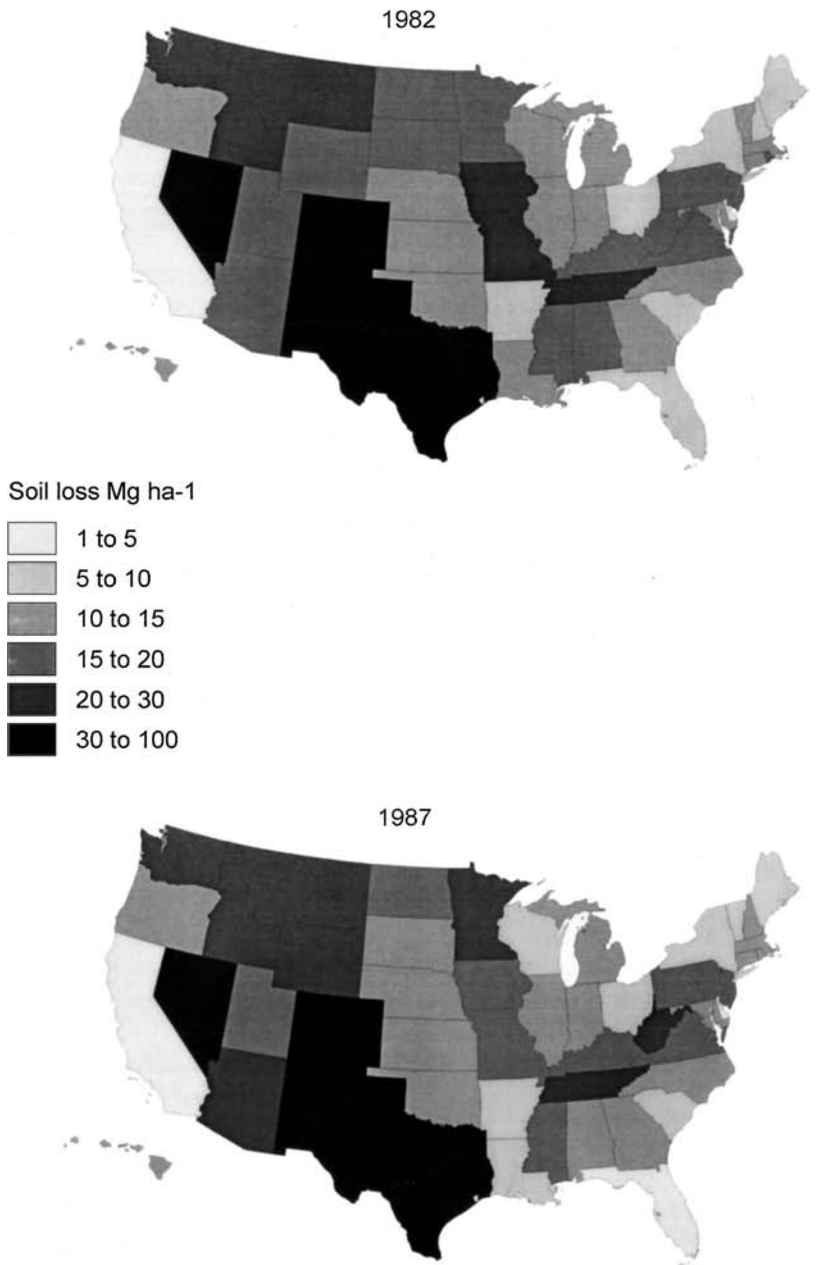

Figure 4 Mean annual wind and water erosion rates on nonfederal, cultivated cropland by state or province, 1982 to 1997 (source: 1997 NRI; Agriculture and Agri-Food Canada, 1998).

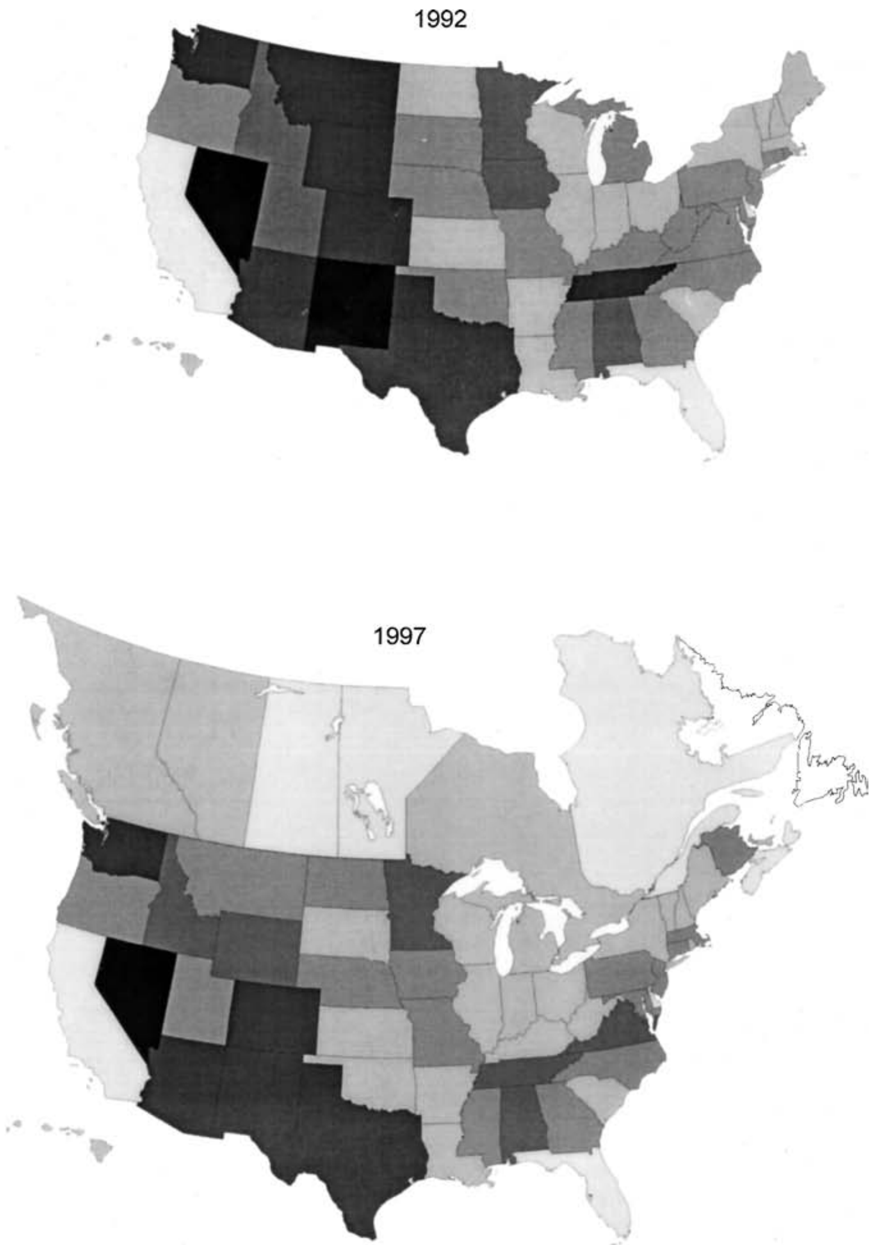

Figure 4 *Continued*

Table II

Total Area of Soil Orders in the United States and Mean Annual Water and Wind Erosion on Cultivated Cropland and CRP on Those Soil Orders[a]

		Mean erosion rate	
Soil order	Area (Mha)	Mg ha^{-1} yr^{-1}	mm ha^{-1} yr^{-1}
Alfisols	126.9	11.5	0.77
Andisols	15.6	5.0	0.33
Aridisols	76.0	25.7	1.71
Entisols	112.2	10.7	0.71
Histosols	15.0	3.3	0.22
Inceptisols	88.9	9.6	0.64
Mollisols	196.7	11.5	0.77
Spodosols	31.8	4.8	0.32
Ultisols	84.2	9.8	0.65
Vertisols	18.2	10.7	0.71

[a]Source: Soil Survey Staff (1999); 1992 NRI.

low as 2.2 Mg ha^{-1} (1 ton acre^{-1}), for most soils they are 11.2 Mg ha^{-1}. Examples of some representative soils are given in Table III. The percentage of land eroding at or below *T* value has increased over time. Based on the 1997 NRI data, average annual sheet and rill erosion in the United States was at or below *T* on 81% of cultivated cropland, up from 73% eroding at or below *T* in 1982. For wind erosion, 85% of cultivated cropland eroded at or below *T* values in 1997 (up from 79% in 1982).

No precise figures for erosion rates are available for Canada. According to a report by Dumanski *et al.* (1994), water erosion exceeded 10 Mg ha^{-1} on 13%

Table III

Tolerable Erosion Loss of Selected Soil Series[a]

Soil series	Soil subgroup	Location	*T* (Mg ha^{-1} yr^{-1})
Fayette	Typic Hapludalf	Wisconsin	11.2
Keene	Aquic Hapludalf	Ohio	9.0
Austin	Udorthentic Haplustoll	Texas	4.5
Marshall	Typic Hapludoll	Iowa	11.2
Shelby	Typic Argiudoll	Missouri	11.2
Cecil	Typic Kanhapludult	Georgia	6.7

[a]Source: Terry (1997).

of Canada's cultivated land in 1986, whereas wind erosion exceeded 10 Mg ha^{-1} on 15% of cultivated land. These figures are comparable to the extent of erosion reported for the United States in the NRI (81 and 85% eroding at or below *T* for water and wind erosion, respectively). A report by Agriculture and Agri-Food Canada (1998) estimated average erosion rates of 4.8 Mg ha^{-1} yr^{-1} for Mollisols and 7.2 Mg ha^{-1} yr^{-1} for Alfisols, which are much lower than the rates of erosion on these soils in the United States. Tomlin and Umphrey (1996) concluded that soil erosion is less severe in Canada than in most other countries because of its temperate climate and the effects of snow cover, a shorter growing season, and a shorter agricultural history. These authors did not see a clear nationwide trend for reduced soil productivity, although yield improvements due to chemical and energy inputs and improved varieties and agronomic practices may be masking the effect of soil degradation.

B. Impact of Erosion on Crop Yields

1. *Maize*

The majority of the studies we reviewed tested the effect of erosion on maize yields. In the United States, erosion–productivity studies on maize were carried out in 18 states, although most of the studies were done in Illinois (27% of the database records), South Dakota (14%), Missouri (11%), and Indiana (9%). Few studies have been conducted in Iowa and Ohio (6% of the records each). In Canada, all erosion–productivity studies on maize were located in southern Ontario.

The mean maize yield across experimental plots in the studies reviewed ranged from 3.3 to 7.8 Mg ha^{-1} (Table IV). The mean yield decline per centimeter of soil loss ranged from 0.04 Mg ha^{-1} on Mollisols to 0.153 Mg ha^{-1} on Ultisols. Mean declines in maize yields are similar on all Mollisols regardless of the experimental method used: 0.054 Mg ha^{-1} cm^{-1} soil loss using depth to fragipan, 0.043 Mg ha^{-1} cm^{-1} using erosion phases, 0.04 Mg ha^{-1} cm^{-1} using TSD, and 0.047 Mg ha^{-1} cm^{-1} in topsoil removal and addition experiments. For Alfisols, the range in yield decline was larger than for Mollisols, ranging from 0.092 Mg ha^{-1} cm^{-1} on TSD experiments to 0.153 Mg ha^{-1} cm^{-1} on experiments using topsoil removal and addition. The mean yield decline in depth to fragipan studies was similar to the mean yield decline in TSD studies, although the range of observed yield declines was larger in the depth-to-fragipan studies. Erosion phase studies reported mean yield declines similar to those in TSD and topsoil removal studies.

The range of mean yield declines reported in the studies was also larger on Alfisols than on Mollisols. Overall, studies using erosion phases as their experimental methods produced the widest range of mean yield declines. Yield declines

Table IV

Impact of Erosion on Maize Yields

Experimental set-up	Soil order	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline (range) (Mg ha^{-1} cm^{-1} soil loss)[a]	Sources[b]
Depth to fragipan	Alfisols	7	3	7.3	0.093 (0.039–0.273)	20, 52, 70, 90
	Mollisols	6	4	7.3	0.054 (0.016–0.093)	24, 41, 52
Erosion phases	Alfisols	42	3	6.5	0.126 (−0.012–1.030)	18, 21, 47, 53, 54, 60, 61, 62, 63, 65, 74, 78, 85
	Mollisols	21	5	7.0	0.043 (−0.080–0.189)	53, 54, 60, 61, 62, 63, 74, 82
	Ultisols	8	3	4.7	0.143 (−0.029–0.336)	66, 77, 86, 87
Topsoil depth	Alfisols	6	3	7.8	0.092 (0.010–0.202)	4, 23, 52, 65, 67
	Mollisols	7	3	5.2	0.040 (−0.009–0.099)	2, 51, 52, 64
	Ultisols	4	4	3.3	0.107 (0.049–0.167)	1, 33, 45, 65
Topsoil removal and addition	Alfisols	9	5	5.9	0.153 (−0.008–0.740)	11, 50, 70, 72
	Mollisols	10	5	6.1	0.047 (0.009–0.094)	2, 9, 24, 27, 40, 49, 55, 63
	Oxisols	2	1	4.0	0.118 (0.097–0.139)	80

[a] Negative numbers in parentheses indicate a yield increase.
[b] See references; numbers correspond to superscripts.

across all studies ranged from −0.012 to 1.03 Mg ha^{-1} cm^{-1} for Alfisols and −0.08 to 0.189 Mg ha^{-1} cm^{-1} for Mollisols (a negative decline indicates that yields were higher on the eroded plots than on the control plots without erosion). Erosion phases and TSD were the only two experimental methods used to determine the impact of erosion on maize yields on Ultisols. The mean yield decline was 0.143 Mg ha^{-1} cm^{-1} soil loss for erosion phase studies compared with 0.107 Mg ha^{-1} cm^{-1} for TSD studies.

In relative terms, maize yield decline was greatest on Ultisols and Oxisols (3% cm^{-1} soil loss compared to 0.7% cm^{-1} for Mollisols). Relative mean yield declines on Ultisols were slightly larger in the TSD studies (3.2%) than in the erosion phase studies (3%), but showed little variation across the experimental methods used on Mollisols (0.6–0.8%). For Alfisols, the relative mean yield declines ranged from 1.3% cm^{-1} in the TSD studies to 2.6% cm^{-1} on the topsoil removal studies. The average yield decline on Alfisols across experimental methods was 1.8% cm^{-1} of soil loss.

Because the studies reviewed in this chapter cover a 50-year time span and are aggregated at the level of soil order, average yields from the experiments in Table IV are lower than those presently achieved on farmers' fields. High-yielding varieties, increased use of fertilizers and pesticides, and improved management practices have led to enormous increases in yields since 1950. These advances are masked, however, by averaging yields over all experimental plots across soil series/subgroups, climatic regions, and time. To examine the possible effects of technological advances, results of studies conducted on maize prior to 1960 were compared to those conducted after 1960. The data in Table V show that mean maize yield of the experiments nearly doubled in studies conducted after 1960, irrespective of soil orders and experimental designs, compared to those prior to 1960.

More importantly, the mean decline in yield per centimeter of soil loss declined on the Alfisol and Mollisol studies, but not on the Ultisol studies. In the TSD experiments, the mean yield decline decreased 32% (from 0.118 to 0.08 Mg ha^{-1} cm^{-1}) in Alfisols and 108% (from 0.059 to −0.005 Mg ha^{-1} cm^{-1}) in Mollisols. In relative terms, mean yield decline decreased from 2.7 to 0.9% in Alfisols and from 1.6 to −0.06% in Mollisols. Although yields of maize grown on Ultisols increased 260% (from 1.79 to 4.73 Mg ha^{-1} yr^{-1}), the mean yield decline per centimeter of soil loss on these soils increased by 171% (from 0.058 to 0.157 Mg ha^{-1} cm^{-1}). The yield decline cm^{-1} of soil loss remained the same in relative terms (3.2 vs 3.3%), though. Last, in the topsoil removal study on a Mollisol, maize yields nearly doubled but yield losses due to soil loss declined in both absolute (from 0.059 to 0.046 Mg ha^{-1} cm^{-1}) and relative terms (from 1.8 to 0.7%). This demonstrates that changes in technology affect not only yields but also yield response to soil loss; for maize, technological advances may reverse some of the effects of soil loss.

Table V

A Comparison of Mean Yields and Yield Impacts Resulting from Erosion in Studies Published before and after 1960

		Before 1960				After 1960 (inclusive)			
Experimental set-up	Soil order	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline [Mg ha^{-1} cm^{-1} (%)]	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline [Mg ha^{-1} cm^{-1} (%)]
Topsoil depth	Alfisols	2	3	4.4	0.118 (2.7%)	4	3	8.7	0.080 (0.9%)
	Mollisols	5	2	3.8	0.059 (1.6%)	2	8	8.8	(−0.005) (−0.06%)
	Ultisols	2	5	1.8	0.058 (3.2%)	2	3	4.7	0.157 (3.3%)
Topsoil removal and addition	Mollisols	1	2	3.3	0.059 (1.8%)	9	5	6.4	0.046 (0.7%)

2. Wheat

Studies which estimated the impact of erosion on wheat yields were primarily conducted in the Palouse region of eastern Washington, eastern Oregon, and Idaho and the Canadian prairie provinces (e.g., Alberta, Saskatchewan, and Manitoba). Most studies were conducted on Mollisols, using topsoil removal and addition as the experimental method. A study on the influence of management practices on soil erosion and wheat yields by Monreal *et al.* (1995) is the longest running experiment included in this chapter. This experiment on an Alfisol in Breton, Alberta comprised 60 years of data, whereas the experiment in Swift Current, Saskatchewan was conducted for 23 years (Table VI).

The mean yield in these studies ranged from 1.6 to 8.0 Mg ha^{-1}, while the mean decline in yield due to soil loss by erosion ranged from 0.005 Mg ha^{-1} cm^{-1} [a wind erosion study by Larney *et al.* (1998) in Lethbridge, Alberta] to 0.143 Mg ha^{-1} cm^{-1} on an Aridisol in Idaho (Table VI). Mean yield decline in TSD studies on Mollisols was 19 kg ha^{-1} cm^{-1} higher than in studies using topsoil addition and removal (0.063 vs 0.044 Mg ha^{-1} cm^{-1}, respectively). The range of yield declines reported in different studies was similar for the TSD studies (0.003–0.225 Mg ha^{-1} cm^{-1}) and the topsoil removal and addition studies ($-$0.033–0.179 Mg ha^{-1} cm^{-1}), even though the yield declines are lower in the topsoil removal studies.

The relative decline in mean wheat yield as a result of soil loss was highest in the study of Monreal *et al.* (1995), which involved different management practices as the experimental method. Mean yield declined 6.4% cm^{-1} of soil loss on Alfisols and 6.7% cm^{-1} on Mollisols. In the topsoil removal studies on Alfisols by Izaurralde *et al.* (1998) and Larney *et al.* (1995), the yield decline was 5.4% cm^{-1} soil loss, which is particularly high, but was obtained from two studies of 1-year duration. Topsoil removal studies on Mollisols resulted in a mean yield decline of 2.3%, obtained from 15 studies with a mean duration of 4 years.

For a few studies on wheat, separate measurements were made to determine the impact of erosion on straw yield. A 10-year study by Rasmussen *et al.* (1991) in Washington showed that wheat straw yield slightly increased (2 kg ha^{-1} cm^{-1} or 0.03%) with decreasing TSD (Table VII), whereas studies by Verity and Anderson (1990), Tanaka (1995), and Larney *et al.* (1995) showed that straw yields declined an average of 110 kg ha^{-1} cm^{-1} (range 0.053–0.187 Mg ha^{-1} cm^{-1}) or 2.7% cm^{-1} of soil removed.

3. Soybeans

The effects of soil loss on yields of soybeans were studied most frequently on Alfisols and Ultisols using erosion phases and topsoil removal and addition as the

Table VI

Impact of Erosion on Wheat Yields

Experimental set-up	Soil order	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline (range) (Mg ha^{-1} cm^{-1} soil loss)[a]	Sources[b]
Management practices	Alfisols	1	60	1.8	0.116	48
	Mollisols	1	23	1.6	0.107	29
Topsoil depth	Alfisols	2	3	8.0	0.028 (0.015–0.041)	4, 42
	Aridisols	1	2	6.7	0.143	10
	Mollisols	14	3	4.2	0.063 (0.003–0.225)	7, 22, 37, 57, 58, 75, 81
Topsoil removal and addition	Alfisols	2	1	2.1	0.114 (0.108–0.119)	31, 38
	Mollisols	42	4	1.9	0.044 (−0.033–0.179)	13, 14, 15, 25, 30, 31, 34, 35, 36, 38, 43, 44, 68, 69, 73

[a]Negative numbers in parentheses indicate a yield increase.
[b]See references; numbers correspond to superscripts.

Table VII

Impact of Erosion on Wheat Straw Yields

Experimental set-up	Soil order	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline (range) (Mg ha^{-1} cm^{-1} soil loss)[a]	Sources[b]
Topsoil depth	Mollisols	1	10	6.5	(−0.002)	58
Topsoil removal and addition	Mollisols	5	3	4.1	0.110 (0.053–0.187)	35, 69, 73

[a]Negative numbers in parentheses indicate a yield increase.
[b]See references; numbers correspond to superscripts.

experimental methods (Table VIII). Mean yields ranged from 0.9 Mg ha^{-1} on an Entisol on a lower coastal plain site in Alabama (McDaniel and Hajek, 1985) to 2.8 Mg ha^{-1} on Mollisols in Indiana (Schertz *et al.*, 1985, 1989) and in the Palouse Hills in Washington (Wetter, 1977). In absolute terms, yield of soybeans appear to be little affected by erosion. Yield decline was less than 40 kg ha^{-1} cm^{-1} of soil loss on all soils except Ultisols, in which mean decline was about 75 kg ha^{-1} cm^{-1} (Table VIII). The ranges of mean yield declines reported in the various studies was also narrow, although the number of records considered is too small to draw any definitive conclusions.

In relative terms, yield declines in these studies ranged from 0.5 to 4.4% cm^{-1} of soil loss. The largest yield losses occurred on Ultisols (4.1 and 4.3% cm^{-1} on erosion phases and TSD studies, respectively) and in TSD studies on an Entisol (4.4% cm^{-1}) and an Inceptisol (3.4% cm^{-1}). The relative mean yield decline in Alfisols was smallest in studies using topsoil removal (0.5% cm^{-1} soil loss) and largest on TSD experiments (1.8% cm^{-1} soil loss). Relative mean yield declines were similar on Mollisols in erosion phase and topsoil removal studies (1.3 and 1.5% cm^{-1}, respectively). The relative decline in yield in Mollisols in Alabama was 3.1% cm^{-1} (Hairston *et al.*, 1989), more than double the decline observed in Mollisols elsewhere. The relative decline computed for this study is similar to that for Entisol and Inceptisol. However, there was only one study on each of these three soils covering a 2-year period.

4. Cotton

The highest relative yield decline of 12% in Table IX was in seed cotton grown on Ultisol in a topsoil removal experiment. This study by Latham (1940), however, is among the earliest erosion–soil productivity studies. The relative decline may

Table VIII

Impact of Erosion on Yields of Soybeans

Experimental set-up	Soil order	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline (range) (Mg ha^{-1} cm^{-1} soil loss)[a]	Sources[b]
Depth to fragipan	Alfisols	3	3	2.1	0.014 (0.013–0.016)	59, 90
Erosion phases	Alfisols	10	5	2.5	0.026 (−0.001–0.070)	16, 18, 60, 61, 74, 89
	Mollisols	3	6	2.8	0.036 (0.033–0.040)	60, 61, 75
	Ultisols	10	3	1.8	0.074 (0.033–0.113)	8, 86, 87
Topsoil depth	Alfisols	1	2	1.9	0.035	45
	Entisols	1	2	0.9	0.040	45
	Inceptisols	1	2	1.1	0.037	45
	Mollisols	1	2	1.2	0.036	26
	Ultisols	3	2	1.8	0.077 (0.072–0.082)	45, 76
Topsoil removal and addition	Alfisols	7	4	2.5	0.013 (0.001–0.041)	56, 71, 72, 79
	Mollisols	2	4	2.7	0.040 (0.040–0.040)	27

[a]Negative numbers in parentheses indicate a yield increase.
[b]See references; numbers correspond to superscripts.

Table IX

Impact of Erosion on Cotton Yields

Experimental set-up	Soil order	Crop	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline (range) (Mg ha^{-1} cm^{-1} soil loss)[a]	Sources[b]
Erosion phases	Ultisols	Cotton	2	3	2.3	0.067 (0.047–0.087)	87
Topsoil depth		Cotton	4	4	1.2	0.040 (0.028–0.054)	1, 45, 65
Topsoil removal and addition		Cotton-seed	1	4	1.0	0.119	39

[a]Negative numbers in parentheses indicate a yield increase.
[b]See references; numbers correspond to superscripts.

be smaller if modern varieties and production technologies were used. The TSD studies in Ultisols with cotton show a mean yield decline of 0.04 Mg ha^{-1} cm^{-1}, or 3.3% cm^{-1}, while in erosion phase studies mean yield decline was 2.7% cm^{-1} (0.067 Mg ha^{-1} cm^{-1}). Absolute yield decline in these studies (Adams, 1949; Stallings, 1957; McDaniel and Hajek, 1985; and Langdale *et al.*, 1987) ranged from 0.028 to 0.087 Mg ha^{-1} cm^{-1} and may provide a more realistic estimation of the impact of erosion on cotton yields.

5. Hay and Fodder Crops

There are six published reports on erosion's impact on the productivity of hay and fodder crops, five of which used TSD as the experimental method and one of which used the topsoil removal and addition method (Table X). Data on fodder grasses in the topsoil removal experiment on Mollisols by Greb and Smika (1985) showed little to no impact of erosion; yield of crested wheatgrass (*Agropyron cristatum* L. Gaertn.) declined 0.013 Mg ha^{-1} cm^{-1} of soil loss (1.7%), whereas that of sudan grass [*Sorghum* sudanense (Piper) Stapf.] actually increased 14 kg ha^{-1} cm^{-1} of soil loss. The yield of russian wildrye [*Psathyrostachys juncea* (Fisch.) Nevski] decreased at an average rate of 2 kg ha^{-1} cm^{-1} of soil loss (0.2% cm^{-1}).

In the TSD experiments, there was a decline in the average yield with progressive reduction of TSD. Mean yield decline was 1.5% cm^{-1} for both vetch (*Vicia sativa* L.) grown on Ultisols (0.247 Mg ha^{-1} cm^{-1}) and alfalfa (*Medicago spp*. L.) grown on Mollisols (0.025 Mg ha^{-1} cm^{-1}). The percentage decline in alfalfa yield grown on Aridisols was about half of that for alfalfa grown on Mollisols (0.8% cm^{-1}), although the measured yield decrease was larger in absolute terms (0.048 Mg ha^{-1} cm^{-1}). Hay yields on Alfisols declined 1.1% cm^{-1} (0.089 Mg ha^{-1} cm^{-1}) and were the same in both studies. The relative impact of erosion on the yield of hay and fodder crops is small, with little variation reported across the limited number of studies on these crops.

6. Miscellaneous Crops

A variety of other crops were studied by researchers on a limited scale. Most of these studies were conducted on one soil series only, and studies were of a 1- to 5-year duration. Six studies investigated the impact of erosion on oat (*Avena sativa* L.) yields, and two studies each involved potatoes (*Solanum tuberosum* L.), beans (*Phaseolus vulgaris* L.), and barley (*Hordeum vulgare* L.). Three studies involved grain sorghum [*Sorghum bicolor* (L.) Moench] (Table XI). Other crops reported on in the literature were silage maize, sugar beets (*Beta vulgaris* L.), and grapes (*Vitis vinifera* L.). Relative mean yield declines were smallest for the root crops: 0.4% for sugar beets on an Aridisol in Idaho (Carter *et al.*, 1985) and 0.6 and 1.0% for potatoes produced on Aridisols and Spodosols, respectively

Table X

Impact of Erosion on Hay and Fodder Yields

Experimental set-up	Soil order	Crop	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline (range) (Mg ha^{-1} cm^{-1} soil loss)[a]	Sources[b]
Topsoil depth	Alfisols	Hay	2	3	7.5	0.089 (0.089–0.089)	4, 65
	Aridisols	Alfalfa	1	2	5.9	0.048	10
	Mollisols	Crested wheatgrass	1	4	2.3	0.021	57
		Alfalfa	1	4	1.7	0.025	57
	Ultisols	Vetch	1	5	15.6	0.247	1
Topsoil removal and addition	Mollisols	Crested wheatgrass	2	1	0.7	0.013 (0.010–0.016)	25
		Russian wildrye	3	3	1.0	0.002 (−0.003–0.009)	25
		Sudan grass	3	2	2.5	(−0.014) (−0.029–0.003)	25

[a]Negative numbers in parentheses indicate a yield increase.
[b]See references; numbers correspond to superscripts.

Table XI

Impact of Erosion on Miscellaneous Crop Yields

Experimental set-up	Soil order	Crop	No. of records	Mean duration of experiments (years)	Mean yield of experiment (Mg ha^{-1})	Mean yield decline (range) (Mg ha^{-1} cm^{-1} soil loss)[a]	Sources[b]
Management practices	Spodosols	Potatoes	1	1	33.5	0.340	12
Erosion phases	Alfisols	Silage maize	1	1	20.8	0.518	32
		Beans	1	1	0.6	0.030	32
		Oats	1	1	1.1	0.063	19
		Sorghum	4	3	5.2	−0.062 (−0.118–0.016)	88
Topsoil depth	Alfisols	Barley	1	4	1.6	0.058	65
		Oats	1	2		0.020	4
	Aridisols	Beans	1	2	2.3	0.040	10
		Barley	1	2	5.4	0.057	10
		Potatoes	1	2	52.7	0.340	10
		Sugar beets	1	2	64.5	0.289	10
	Inceptisol	Grapes	1	2	7.8	0.32	3
	Ultisols	Oats	2	5	2.5	0.061 (0.043–0.080)	1, 65
Topsoil removal and addition	Mollisols	Sorghum	12	3	3.7	0.052 (0.006–0.108)	17, 83
		Oats	1	2	2.1	0.017	49

[a]Negative numbers in parentheses indicate a yield increase.
[b]See references; numbers correspond to superscripts.

(Carter *et al.,* 1985; DeHaan *et al.,* 1999). The yield declines of the four crops tested by Carter *et al.* (1985) were smaller, both in absolute and relative terms, than the yield declines of crops grown on other soils. The absolute yield decrease in barley on the Aridisol and the Alfisol (Table XI) was about the same (0.057 and 0.058 Mg ha^{-1} cm^{-1}, respectively), but in relative terms the decline was much smaller (1.1%) on the Aridisol than on the Alfisol (3.7%). The difference in yield, however, cannot be solely attributed to a difference in soils; the study on Aridisols was conducted in the 1980s, whereas that on the erosional impact on barley yield on the Alfisol dates from 1957. Advances in crop management and the availability of high-yielding barley varieties led to higher yields, decreasing the relative decline in yields resulting from erosion. The results of studies on sorghum are mixed; topsoil removal and addition studies on Mollisols by Eck (1968, 1987) and Eck *et al.* (1965) in Texas show a 1.4% decline in yields, whereas a study using erosion phases on Ultisols by Langdale *et al.* (1987) in Georgia showed that yields increased 1.2% cm^{-1} soil loss.

Erosion's effects on oats were studied by six researchers on three soils using three experimental methods. Mean yields of all experiments ranged from 1.1 to 2.5 Mg ha^{-1} [no yield data were reported by Barre (1939)], and yield decline ranged from 0.017 to 0.063 Mg ha^{-1} cm^{-1} (Table XI). The relative yield decline was smallest in a topsoil removal study on Mollisols (0.8%) by Murray *et al.* (1939) and highest on an erosion phases study on an Alfisol (5.8%) by Fenton *et al.* (1971).

V. CROP PRODUCTION LOSS DUE TO EROSION IN NORTH AMERICA

Based on the average decline in yield of different crops for each centimeter of soil loss presented in the previous section, we calculated the potential loss of production due to erosion. Susceptibility to erosion differs among soils (Table II). The loss of 1 cm of soil may occur faster on Aridisols (eroding at an average rate of 25.7 Mg ha^{-1} yr^{-1}) than on Alfisols and Mollisols (eroding at an average rate of 11.5 Mg ha^{-1} yr^{-1}). For the United States, we calculated the annual loss of production using the average erosion rates by soil orders from Table II. For Canada, calculations are based on average annual erosion rates of 4.8 Mg ha^{-1} for Mollisols and 7.2 Mg ha^{-1} for Alfisols (Agriculture and Agri-Food Canada, 1998). The results of the calculations are shown in Table XII for the United States and Table XIII for Canada.

In the United States, the maximum potential crop production lost annually through accelerated erosion is 229×10^3 Mg of maize, 54×10^3 Mg of wheat,

Table XII

Potential Annual Loss in the Production of Maize, Wheat, Soybean, and Cotton in the United States as a Result of Erosion

Crop	Soil order	Area in crop[a] (Mha)	Mean yield[a] (Mg ha^{-1})	Mean yield impact[b] [Mg ha^{-1} cm^{-1} (%)]	Annual loss of production[c] [10^3 Mg (%)]
Maize	Alfisols	10.8	7.5	0.133 (1.8%)	111.1 (0.14%)
	Mollisols	17.7	7.9	0.048 (0.8%)	86.1 (0.06%)
	Ultisols	2.8	5.8	0.131 (3.1%)	32.0 (0.2%)
Soybeans	Alfisols	7.7	2.4	0.021 (0.9%)	12.9 (0.07%)
	Mollisols	10.9	2.7	0.037 (1.5%)	33.5 (0.12%)
	Ultisols	2.9	1.8	0.075 (4.2%)	13.8 (0.27%)
Wheat	Alfisols	3.4	3.1	0.028 (0.4%)	3.2 (0.03%)
	Mollisols	20.5	2.3	0.054 (1.4%)	50.4 (0.11%)
Cotton[d]	Ultisols	0.8	1.1	0.049 (3.1%)	1.9 (0.2%)

[a]Mean of 1987, 1992, and 1997 U.S. agricultural census data.
[b]Decrease in yield is calculated as the percentage of mean experimental yield across experimental methods (Tables III, V, and VI).
[c]Based on average annual erosion rates of 11.46, 11.54, and 9.78 Mg ha^{-1} yr^{-1} on Alfisols, Mollisols, and Ultisols, respectively (1992 NRI data) and assuming a bulk density of 1.5 Mg m^3.
[d]Cotton production is reported in bales in the census; conversion to megagrams is based on mean bale weight of 217.72 kg.

Table XIII

Potential Annual Loss in the Production of Maize, Wheat, and Soybean in Canada as a Result of Erosion

Crop	Soil order	Area in crop[a] (Mha)	Mean yield[b] (Mg ha^{-1})	Mean yield impact[c] [Mg ha^{-1} cm^{-1} (%)]	Annual loss of production[d] [10^3 Mg (%)]
Wheat	Alfisols	0.36	2.5	0.114 (5.7%)	2.5 (0.27%)
	Mollisols	9.90	2.2	0.047 (2.7%)	19.0 (0.09%)
Maize	Alfisols	1.05	7.0	0.073 (1.5%)	5.3 (0.07%)

[a]Source: 1996 Census of Agriculture, Statistics Canada.
[b]Sources: Ontario Ministry of Agriculture, Food and Rural Affairs; Alberta Department of Agriculture, Food and Rural Development; Saskatchewan Department of Agriculture and Food; Manitoba Department of Agriculture and Food; and Quebec Ministry of Agriculture, Fisheries and Food.
[c]Decrease in yield is calculated as the percentage of mean experimental yield across experimental methods (Tables III, V, and VI).
[d]Based on average annual erosion rates of 7.2 and 4.8 Mg ha^{-1} yr^{-1} on Alfisols and Mollisols, respectively (Agriculture and Agri-Food Canada, 1998) and assuming a bulk density of 1.5 Mg m^{-3}.

61×10^3 Mg of soybeans, and 1.9×10^3 Mg of cotton, respectively (Table XII). The relative decline in production ranges from 0.03 to 0.3% yr^{-1}, or 0.9 to 11.6 kg ha^{-1} yr^{-1}. Production loss is low for soybeans and wheat on Alfisols (0.07% yr^{-1} and 0.03% yr^{-1}, respectively) and maize on Mollisols (0.06% yr^{-1}). Production losses are intermediate for maize on Alfisols (0.14% yr^{-1}) and soybeans and wheat on Mollisols (0.12% yr^{-1} and 0.11% yr^{-1}, respectively). Crops grown on Ultisols show the highest decline in production as a result of erosion; relative production loss of maize, soybeans, and cotton on these soils is 0.2% yr^{-1}, 0.27% yr^{-1}, and 0.2% yr^{-1}, respectively. At 2000 prices (USDA, 1999), these losses represent a total value of U.S.$37.9 million for the selected crops and soil orders. Scaling up to account for the additional acreage of these crops that is grown on soils other than Alfisols, Mollisols, and Ultisols, an estimate annual loss of U.S.$55.6 million is generated for the United States as a whole. This figure, based on rates of erosion distinguished spatially by crop and soil order, is about 25% lower than the U.S.$82.9 million estimate that results from applying the 1992 average erosion rate across all soils and crops. The latter figure would be even higher if the 1982 average erosion rate was used.

For Canada, the maximum potential production loss is 5.3×10^3 and 21.5×10^3 Mg for maize and wheat, respectively (Table XIII). Using the same prices as for the United States, this translates into a loss of U.S.$3.2 million per year for the selected crops and soil orders. Relative production loss is less than 1/10th of 1% for maize on Alfisols (0.07% yr^{-1}) and wheat on Mollisols (0.09% yr^{-1}). Annual production loss of wheat grown on Alfisols in Canada, however, is more than four times higher than that on Mollisols (0.27% yr^{-1}). This difference may be due to the different types of wheat grown on these soils: winter wheat on Alfisols and spring wheat on Mollisols.

In both countries, these aggregate losses to producers conceal spatial differences that are potentially significant. Further GIS analysis would enable identification of these differences across soil suborders, crops, and erosion rates. In addition to these productivity losses, the off-site societal costs of erosion are also potentially significant (Crosson 1986, 1997; Ribaudo, 1989).

VI. ASSUMPTIONS

Most studies relating crop productivity to soil erosion reviewed in this chapter were based on two assumptions: (1) All soil properties of the experimental site were similar when first cultivated and (2) the productivity of the site was uniform until erosion occurred (Daniels *et al.*, 1987). These assumptions relate any reduction in yield to differences in TSD and thus to erosion severity. Williams and Tanaka

(1996), however, showed that, at least in the Northern Great Plains, differences in TSD on the landscape are not entirely due to soil erosion. Soils within a landscape or even within one field can have varying TSD and solum thickness, sometimes even within small distances. The soils in some positions on the landscape may not have developed as thick of an A-horizon or as mature a soil profile due to different rates of soil formation caused by differences in topography and climate. The assumptions of uniform soil properties and equal productivity, therefore, are usually not valid (Daniels *et al.,* 1987). Research by Lamb *et al.* (1995, 1997) in Minnesota; Halvorson (1999) at the Kellogg Biological Station near Battle Creek, Michigan; and Karlen *et al.* (1990) in South Carolina showed great variability in yields over space and time. These researchers found that yields were not spatially consistent over time, i.e., areas with good and poor yields were not similar among years. Crop yield differences on eroded and slightly eroded soils, therefore, may not be the result of TSD differences due to erosion alone. Nevertheless, erosion does have adverse effects on yields, but the precise mechanisms are not yet well understood.

A. Range of Experimental Methods, Management Practices, and Time Periods

The principal limitation of estimating productivity loss from the available literature is that data are obtained from a range of experimental methods and management practices over varying time periods. While the impact on crop yields and production losses appear to be similar for the different methods used, they are not directly comparable. Topsoil removal and addition experiments provide a measure of the potential impact of future erosion, whereas the other methods reflect the effects of past erosion. Each of these methods has inherent strengths, weaknesses, and biases that can result in the measured soil productivity response attributed to erosion being potentially confounded with other variables (Olson *et al.,* 1994). For a description of the various methods employed in soil erosion–productivity studies, as well as their strengths and weaknesses, we direct the readers to NSESPRPC (1981), Rijsberman and Wolman (1984), Follett and Stewart (1985), Lal (1987, 1997, 1998), Larson *et al.* (1990), and Olson *et al.* (1994). Despite these differences, for this analysis it was necessary to assume that the results of the studies were comparable.

The studies considered in this chapter were carried out over a range of time periods, ranging from 1 to 60 years. Ninety percent of the studies included in this chapter had a duration of 5 years or less; of these, 29% had a duration of 1 year and 28% had a duration of 2 years. Only 4% of the studies collected data over a period of more than 10 years [studies by Alberts and Spomer (1987) and Monreal *et al.*

(1995)]. According to Rijsberman and Wolman (1984), a period sufficiently long to show the effect of erosion on yields would generally be more than 10 years. Even with data over such a time period available, these authors argue that it would not be easy to distinguish trends in yields as a result of erosion from trends as a result of, for example, changes in technology, pest and disease incidence, and climate. Regarding climate, there may be considerable year-to-year variation in yields due to weather. In dry years, this may result in significant decreases in yield on eroded plots, whereas in years with abundant rainfall, yields of eroded plots may be the same (and in some cases be higher) than the yield on the uneroded control plots. Shaffer *et al.* (1994), therefore, concluded that even 3 to 6 years of data may not be adequate to describe long-term climate impacts on crop response to erosion.

B. Differential Relationships between Degradation and Yields

For ease of analysis and comparison of the data, we assumed that the relationship between soil degradation and soil productivity was linear for all cases. In reality, linear relationships are seldom found (Hopkins *et al.*, personal communication). On Alfisols and Ultisols, Latham (1940) found that yield declines from the first few centimeters of soil loss are usually greater than yield declines from subsequent soil loss. In contrast, research on Mollisols by Odell (1950), Tanaka and Aase (1989), and Verity and Anderson (1990) and on Vertisols by Hairston *et al.* (1989) and Miller *et al.* (1985) showed that yield declined gradually until a minimum, critical TSD was reached, after which a more rapid decrease in yield was observed. Massee (1990) and Larney *et al.* (1995) found that wheat yields related exponentially to depth of topsoil on Mollisols in Idaho and quadratically on six Mollisols in Alberta respectively.

Productivity decline, therefore, is usually not linear with respect to soil loss, but the precise nature of the relationship is specific to the soil type and the environment (Stocking and Peake, 1985). Yield–degradation relationships may also not remain the same over the duration of the experiment because of fluctuations in climate or other, noncontrolled variables. Swan *et al.* (1987) found that the relationship of corn yield to soil depth to residuum on Rozetta and Palsgrove soil series in Wisconsin was dependent on the year selected for measurement and on the associated climatic conditions that occurred during the growing season. Swan *et al.* go on to say that because the yearly depth–yield relationships are so strongly dependent on climatic conditions, accurate determination of the long-term effect of depth on yield must be based on a statistically sound representation of climatic conditions. With a limited number of years of observation, averaging the yearly depth–yield relationships may, therefore, not provide an accurate estimate of yield because of the variable yields observed between years.

C. Effects of Technological Advances

During the roughly 60 years covered by the studies included in this chapter (from 1939 to 1999), agricultural production practices have changed dramatically, increasing yields in spite of nationwide erosion rates that were well above tolerance levels for much of this period. For example, maize yields in Pottawattamie County, Iowa, increased at a rate of 0.037 Mg ha^{-1} yr^{-1} between 1929 and 1953 and 0.145 Mg ha^{-1} yr^{-1} during the 1957-to-1970 period (Spomer and Piest, 1982). Overall, crop output increased at an annual rate of 2% between 1948 and 1994 (Ahearn *et al.*, 1998). The increase in yield is highly correlated with the increased use of fertilizers and agrichemicals; U.S. fertilizer use increased at an annual rate of 1.72% in the 1948-to-1994 period, while pesticides use grew at a compound annual rate of 4.73% during this period (Ahearn *et al.*, 1998). The growth in fertilizer use was especially high in the 1970s: 4.73% per annum.

The increasing use of chemical fertilizers and pesticides together with mechanization and the use of high-yielding hybrid varieties enabled drastic increases in yields and in production. However, the increase in crop yields made possible by science and technological advances may be masking the effects of erosion on long-term soil productivity (Lindstrom *et al.*, 1986; Spomer and Piest, 1992; Ponzi, 1993; Dregne, 1995). Krauss and Allmaras (1982) and Kaiser (1967) concluded that wheat yields in the Palouse region of the northwestern United States would have been 22% higher in 1976 if the area had not experienced 90 years of excessive erosion. Actual yields on eroded sites had increased as a result of technological advances, despite the erosion.

VII. IMPLICATIONS FOR RESEARCH AND POLICY

The amount of erosion occurring on U.S. cropland decreased between 1982 and 1997 as a result of the retirement of the most highly erodible land and the increasing use of conservation tillage. In 1997, the majority of cultivated cropland in the United States and Canada[1] eroded at or below tolerable rates, translating into a soil loss of $\leq$0.8 mm yr^{-1}.[2] In general, the studies reviewed showed a decrease in productivity with accelerated soil erosion. Our results, therefore, concur with findings of earlier reviews of the relationship between soil erosion and productivity. The decline in yield, however, is not the same for different soils and crops.

---

[1]Erosion risk classes in Canada are different from those in the United States. Very low, or tolerable, rate is <6 Mg ha^{-1} yr^{-1}, while a low rate equals 6–11 Mg ha^{-1} yr^{-1} (Wall *et al.*, 1997).

[2]Assuming bulk densities of 1.5 g cm^3 and annual erosion at a rate of T (11.2 Mg ha^{-1}), 1 cm of soil would be lost in 13.3 years.

A. Decline in Crop Yields

In general, for the various crops tested in the experiments, Mollisols recorded a smaller decline in yield due to erosion than Alfisols and Ultisols (in that order). In the United States, the average annual yield decline due to accelerated erosion for maize was 0.15% on Alfisols, 0.06% on Mollisols, and 0.2% on Ultisols. In Canada, maize yields declined 0.07% yr^{-1} on Alfisols. Overall, wheat yields declined by 0.03 and 0.11% yr^{-1} on Alfisols and Mollisols in the United States and 0.27 and 0.09% yr^{-1} on Alfisols and Mollisols in Canada as a result of erosion. In several studies, maize and wheat yields on Mollisols actually increased on moderately and severely eroded plots compared to slightly or noneroded plots.

The relative wheat yield declines per centimeter of soil loss are higher in Canada than in the United States for similar soils. The reasons for this are not clear, but we surmise that some of the difference may be a result of aggregating soils at the soil order level. This aggregation may mask differences between soils that could become apparent at a lower level of aggregation (e.g., soil subgroup or soil series). Interactions with other factors (notably climate, management, and varieties) may also cause some of the observed differences. Average soybean yield declined 0.07, 0.12, and 0.27% yr^{-1} on Alfisols, Mollisols, and Ultisols, respectively, whereas average cotton yields on Ultisols declined 0.2% yr^{-1}. The number of studies on other soil orders (Inceptisols, Entisols, and Aridisols) were too few in number to make any definite conclusions about the impact of erosion; the studies that have been done on those soils generally show a decrease in productivity with accelerated erosion. Similarly, the number of studies using crops other than maize, wheat, soybeans, or cotton is too small to draw conclusions as to how erosion affects their yields.

With the steady increase in crop yields over time due to technological advances, the relative reduction of yields per centimeter of soil loss has declined. A comparison of pre- and post-1960 studies on maize in the present chapter revealed that the absolute yield loss per centimeter of soil erosion declined as well on both Alfisols and Mollisols, but not on Ultisols. On Ultisols, both yield and erosion-induced loss of yield of maize increased so that the relative yield decline per centimeter of soil loss remains the same. A comparison of yields across time periods for other crops was not possible. Nevertheless, this finding has important implications for using the results of soil erosion–productivity studies to make predictions about the impact of erosion. First, this comparison shows that, at least for maize, technology can reverse some of the productivity decline due to erosion as revealed in the narrowing of the yield gap between slightly and severely eroded soils. Second, if the impact of erosion on yield (a measure of historical production used as a proxy to determine the potential for future production) changes due to technological advances as revealed in smaller absolute and relative declines in yield per centimeter of soil loss, then continued use of the results of "old" studies may exaggerate estimates of the impact of erosion on productivity. Continuing research to monitor the effects of erosion on soil productivity is, therefore, necessary.

B. Productivity and Economic Impact

The amount of production decline resulting from erosion in North America equals 234.5×10^3 Mg yr^{-1} of maize, 60.2×10^3 Mg yr^{-1} of soybeans, 75.0×10^3 Mg yr^{-1} of wheat, and 1.9×10^3 Mg yr^{-1} of cotton. These figures represent the maximum potential annual losses due to accelerated erosion based on the assumption that soil is lost to a uniform depth over the entire field surface. The total economic value of erosion-induced loss of soil productivity on Alfisols, Mollisols, and Ultisols in North America (using 2000 prices) amounts to U.S.$41.2 million per year, U.S.$37.9 million for the United States and the remainder in Canada. To the extent that commodity prices increase as a result of erosion-induced declines in production, the value of production losses would be higher than we estimated using 2000 prices.

As these crops are also grown on other soil orders, the economic impact for North America as a whole is larger. We estimate that the economic impact for Canada is fairly accurate, as little wheat and maize are produced on soil orders other than Alfisols and Mollisols. However, the estimated cost of yield losses due to erosion in Canada of U.S.$3.2 million is smaller than previous estimates by Sparrow (1984) and Dumanski *et al.* (1986, 1994). For the United States as a whole, based on the ratio of the area of maize, soybeans, wheat, and cotton on Alfisols, Mollisols, and Ultisols to the total area for these crops, the total annual economic impact of erosion on these crops is estimated at U.S.$55.6 million. Finer spatial resolution has improved this figure from the estimate of U.S.$82.9 million that results from application across all soils of the 1992 U.S. average erosion rate. This figure is smaller than earlier estimates by Alt *et al.* (1989), Crosson (1986), and Pimentel *et al.* (1995), but similar to estimates by Larson *et al.* (1983) and Crosson (1997). The costs in lost yields, however, are only a part of the total costs incurred by farmers, as they do not include the costs incurred to reduce or offset the yield effects of erosion (Crosson, 1997).

On a per-hectare basis, reflecting the unit of farmer decision making about erosion-mitigating practices, the annual impact of erosion on crop yield is small, ranging from <1 kg ha^{-1} for wheat on Alfisols in the United States to 11.6 kg ha^{-1} for maize on Ultisols. The annual economic losses per hectare experienced by farmers in North America are correspondingly small: U.S.$0.39–0.95 ha^{-1} yr^{-1} for corn, U.S.$0.12–0.88 ha^{-1} yr^{-1} for wheat, U.S.$0.28–0.80 ha^{-1} yr^{-1} for soybeans, and U.S.$2.53 ha^{-1} yr^{-1} for cotton. Because of the multiple factors affecting crop yields, it may be difficult for a producer to distinguish the annual yield loss due to erosion (e.g., for maize 5 to 12 kg ha^{-1} and for wheat 1–7 kg ha^{-1}) from yield variations due to climate, pests and diseases, varieties used, and management practices. In view of (still) increasing yields as a result of crop varietal improvements, chemical and energy inputs, and improved agronomic practices, it may, therefore, be difficult to convince farmers of the seriousness of productivity loss. However, the decrease in yield is cumulative and may cause a noticeable impact if erosion continues unabated over a long period of time. The small annual declines in productivity and economic value provide relatively weak incentives for farmers to adopt erosion-mitigating practices. This underscores the importance of policy measures to encourage the adoption of practices necessary to reduce the off-site effects of erosion. As Crosson (1986) showed, these off-farm effects of erosion are several multiples, if not an order of magnitude, of the on-farm costs. A second implication is that, while estimated aggregate economic losses are relatively small, these aggregates conceal potentially significant geographic variations. Locally, losses may be very high; further GIS analysis will be necessary to reveal such spatial differences.

Soil erosion and yield loss can be reduced or halted by improvements in technology and management practices, but unless these are demonstrated to be economic they are unlikely to be adopted even though desirable from the standpoint of society. It may also be unrealistic to expect an agriculture without any erosion. Even if this was feasible, it would not necessarily be economical. A certain, at times perhaps very high, level of erosion may be accepted by farmers until it becomes cost-effective to mitigate its adverse effects as yield decreases resulting from the loss of soil start reducing farm profits. This does not mean that farmers are unconcerned about maintaining their resources; on the contrary, the preservation of soil and water resources is considered a primary farm goal by a majority of Midwest producers, both conventional and sustainable (den Biggelaar and Suvedi, 1998; Geisler and den Biggelaar, 1998). Decisions about cropping and management practices by producers will depend foremost on their ability to survive economically (IISD 1999). Farmers do not explicitly choose a level of soil loss (i.e., the *amount of soil* loss is not the decision variable). Rather, they make crop, rotation, input, and management decisions that result in a particular soil loss (Furtan and Hosseini, 1999). The decision processes employed by farmers about mitigating soil degradation are, however, still not well understood and require additional research.

C. Factors Confounding the Effect of Erosion on Productivity

Within soil orders, large variations in yields and in the relationship between yields and soil erosion were observed. Yield variations occurred both over space and over time. In several studies, researchers found that yield levels between eroded and uneroded phases were not significantly different in years of normal or above-normal rainfall, or when irrigation was used, indicating that water and water-holding capacity of the soil may become limiting as degradation progresses. Weather and climatic factors, therefore, may play a more important role in determining crop yields than soils. Simmonds (1979), Johnston *et al.* (1998), Lamb *et al.* (1997), and Haji and Hunt (1999) also found that the effect of year (climate) on crop yield was greater than that of the location.

In addition to varying amounts of erosion, Daniels *et al.* (1985, 1987), Hoag (1998), Larson *et al.* (1990), and Wright *et al.* (1990) observed that the position of experimental plots within a landscape needs to be considered to explain observed yield differences between plots representing different erosion phases or soil depths. In several recent studies, large, spatially inconsistent annual variations in yields were observed within one field (Lamb, 1995, 1997; Timlin, 1998) or within one experimental plot (Halvorson, 1999). That is, high and low yields were not consistently found in specific locations within a field or plot. As soil properties change only slowly over time, and as climatic and management differences can be assumed to be minimal within one contiguous field or experimental plot, perhaps the practice of attributing yield loss solely to a decrease in TSD, an assumption used in most erosion-productivity studies, needs to be revisited. Plant growth and yield are generally related to the most limiting individual factor, and limiting factors may change with accelerated erosion over time and as a result of management.

A number of studies reviewed were multifactorial in design, with erosion levels in the main plots and varying amounts of fertilizers in subplots. The subplots were included to determine the amount of fertilizers necessary to restore the productivity of eroded phases to the same levels of those of uneroded soil. Nutrients applied by themselves, however, may not be enough to maintain productivity if other factors becoming limited are not taken into consideration. In several (but not all) studies, the investigators concluded that no amount of fertilizers would be able to restore productivity levels lost as a result of erosion. Nevertheless, other factors may have become limiting when nutrient levels were boosted in these studies, although this was neither acknowledged nor investigated further. Further studies are required to determine which factors become limited when nutrient levels (or other factors) are increased on erosional phases, and their effect on crop yields. Such studies require systemic, ecological methods to determine the effects of erosion and management on soil properties and to determine how changes in soil properties affect crop yields.

According to Rijsberman and Wolman (1984), crop yield is only a good estimator of the differences in productivity between two soils, or between eroded phases of one soil, when (a) the same crop is used and (b) this crop is the “optimal” crop for both soils (or soil phases). The assumption that one crop is optimal for all erosional phases of a soil is unproven. It may well be that the optimal crops for slightly, moderately, and severely phases are not the same; from a management perspective, it is, however, difficult, if not impossible, to produce different crops on the various phases using modern production practices and technologies. The micromanagement of resources by growing specific crops and crop varieties to particular soils and soil phases is not uncommon in small-scale agriculture in developing countries, as observed by den Biggelaar (1994) in Rwanda. Precision farming, however, is a move to increase micromanagement of the soil resource, using varying management practices within one single crop rather than using different crops. Second, even if we use the same crop on a particular soil, and if this crop is optimal for this soil and its various phases, it is not necessarily true that the same *variety* of this crop is optimal for both eroded and uneroded phases of this soil. No studies were found that tested the differential response of crop varieties to accelerated erosion, at least not deliberately and systematically. The identification and/or development of varieties specifically adapted to perform well on eroded soils and soil phases may offer an alternative to trying to restore soil properties to their original uneroded equivalent (if we even *can* know the productivity of uneroded soil) with external inputs and variable management practices.

Although a decrease in soil depth (in whatever form) was used as the predictor for productivity losses in the studies reviewed here, and some researchers found highly significant correlations between depth and yields, there was a great variation in the observed relationships due to years, soils, climate, and management. As shown in Fig. 1 and discussed in Section II,B, there are many factors affecting crop yields, soil depth being only one of them. Given the variability of research results, soil depth by itself does not appear to be a sufficient determinant of decreasing productivity. Erosion does not only lead to a decrease in (top-)soil depth, but causes a host of other changes in the soil that may provide better answers for why yields decline with accelerated erosion over time. Additional research is, therefore, necessary to (1) determine if productivity losses are permanent (Cann *et al.*, 1992) and (2) investigate the spatial relationships between soil variability and yields within a landscape and the variability and stability of yield across a field/plot such as the compensatory effects of depositional sites (Fahnestock *et al.,* 1995). This will require studies of localized TSD–yield response relationships to typify specific soils, climates, and landscapes (Cann *et al.,* 1992), especially in areas with high erosion rates where economically important crops are produced. Bruce *et al.* (1987) believe that soil orders are too inclusive and can lead to contradictory data interpretations. They suggest using soil family as the classification level, as it is at this level that one can identify soil features useful in describing the potential effect of soil erosion on productivity. Yield monitors installed on crop harvesters, GPS, and GIS can be used for this purpose, but it will also require intensive soil surveys to link observed yields with soil physical, chemical, and biological properties as well as climate and management data. Geographic information systems can be used to manage the amount of data necessary for this analysis, which would result in more precise estimations of the productivity impact of erosion at a greater resolution than was done in this and previous reviews. Continuing the list, additional research is needed to (3) develop methods to detect long-term productivity loss in the face of yield increases due to technological advances, (4) determine how different types of soil degradation are interrelated (Cann *et al.*, 1992), and (5) investigate farmers' decision-making processes when estimating actual impacts as opposed to potential impacts determined by soil erosion–productivity research.

VIII. CONCLUSION

Several features of the estimated aggregate annual economic losses in productivity due to soil erosion are important. First, the low rate of erosion-induced productivity loss in North America reflects the impact of improved technology, especially of the increased use of fertilizers and other amendments and improved crop varieties. Second, losses estimated using soil-specific erosion rates are smaller than those estimated using national-average erosion rates. Our estimate of U.S.$55.6 million in aggregate annual erosion-induced losses for the selected crops is about 25% lower than the U.S.$82.9 million estimate that results from applying the 1992 average erosion rate across all soils and crops (the latter figure would be over U.S.$100 million at the 1982 average erosion rate). These losses are smaller than those estimated by others, including Sparrow (1984), Crosson (1986), Alt *et al.* (1989) Dumanski *et al.* (1994), and Pimentel *et al.* (1995). Each of those studies were based on data collected in the 1970s and 1980s, when erosion rates were significantly higher than they are today. Agricultural prices have also been following a downward trend in recent years, reducing the economic impact of yield losses. Our results are, however, comparable to estimates by Larson *et al.* (1983b) and Crosson (1997).

Third, current estimated losses are small relative to the total value of agricultural production of these crops. As such, they are likely to be masked over the short term by interannual variation in yields and net returns that arise from weather, pests, and market conditions. As a result, the effects of erosion can be expected, on average, to provide farmers with relatively weak incentives to adopt erosion-mitigating conservation practices in the short run.

Fourth, estimated losses in productivity are small relative to the off-site costs of erosion estimated by others, including Crosson (1986) and Ribaudo (1989), in terms of water quality and other impacts.

Each of these features underscores the success of past policy measures in providing farmers with incentives to adopt soil conservation measures, and the importance of continued policy efforts to promote such adoption in the future, in order to realize conservation goals that are important to society as a whole and to sustain productivity levels over the long term. They also underscore the importance of further attention to spatial variation in the impacts of soil erosion both on-site and off-site. Specifically, the aggregate magnitude of estimated losses is less significant than the variation in impacts that are revealed by crop and soil order.

Furthermore, such variation indicates that the distribution of existing studies of erosion's impact on productivity directs insufficient attention to several geographic areas where the combination of crop production, erosion rates, and yield impacts generate relatively large impacts. Future analysis of variation in impacts at finer spatial resolution will permit improved identification of problem areas that are concealed at coarser scales as well as improved targeting of policy incentives.

Additional research is also needed on farmers' responses to erosion and other forms of soil degradation. The estimates provided in this chapter (and in the individual studies on which our analysis is based) are based on the assumption that farmers' practices are held constant. Over time, of course, practices do change in response to changing circumstances. More precise estimation of actual yield losses or cost increases that will be realized as a result of erosion (as opposed to the potential losses estimated here) will depend on improved understanding of how farmers' optimal choices will vary in the face of changing physical, market, and policy environments.

Acknowledgments

The views expressed here are those of the authors, and may not be attributed to Appalachian State University, The Ohio State University, or the Economic Research Service. Helpful comments from Jeff Hopkins and Meredith Soule are gratefully acknowledged.

References[a]

[1]Adams, W. E. (1949). Loss of topsoil reduces crop yields. *J. Soil Water Cons.* **4**(3), 130.

Agriculture and Agri-Food Canada (1998). Section 5: Environmental Assessment. *In* "The Federal-Provincial Crop Insurance Program. An Integrated Environmental-Economic Assessment." Internet URL: http://www.agr.ca/policy/epad/english/pubs/adhoc/98009rtoc.htm.

Ahearn, M., Yee, J., Ball, E., and Nehring, R. (1998). "Agricultural Productivity in the United States," Agric. Info. Bull. 740. USDA Economic Research Service, Washington, DC.

[2]Alberts, E. E., and Spomer, R. G. (1987). Corn grain yield response to topsoil depth on deep loess soil. *Trans. ASAE* **30**(4), 977–981.

[3]Alderfer, R. B., and Fleming, H. (1948). Soil Factors Influencing Grape Production on Well-drained Lake Terrace Areas. *Pennsylvania Agric. Exp. Stn. Bull.* 495, State College, PA (24 pp.).

Alt, K., Osborn, C. T., and Colacicco, D. (1989). "Soil erosion: What Effect on Agricultural Productivity?" Agric. Info. Bull. 556. USDA Economic Research Service, Washington, DC.

American Society of Agricultural Engineers (ASAE) (1985). "ASAE Special Publication 85-8: Erosion and Soil Productivity," pp. 28–38. American Society of Agricultural Engineers, St. Joseph, MI.

Anderson, D. W., and Gregorich, E. G. (1984). Effect of soil erosion on soil quality and productivity. *In* "Proceedings, Second Annual Western Provincial Conference Rationalization of Water and Soil Research and Management: Soil Erosion and Land Degradation, Saskatoon, SK, November 29 to December 1, 1983," pp. 105–113. Saskatchewan Institute of Pedology, Saskatoon, SK.

[a]Superscript numbers in front of references refer to the sources in Tables IV to XI.

[4]Barre, R. D. (1939). Effect of erosion on crop yields. Supplement to Muskingum Watershed Ohio survey report: Runoff and water retardation and soil erosion prevention for flood control: Appendix X. *In* "Soil Conservation" (J. H. Stalling, Ed.), pp. 195–220. Prentice-Hall, Englewood Cliffs, NJ.

[5]Battiston, L. A., Miller, M. H., and Shelton, I. J. (1987). Soil erosion and corn yield on Ontario I. Field evaluation. *Can. J. Soil. Sci.* **67,** 731–745.

[6]Battiston, L. A., McBride, R. A., Miller, M. H., and Brklacich, M. J. (1985). Soil erosion–productivity research in southern Ontario. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 28–38. American Society of Agricultural Engineers, St. Joseph, MI.

Bennett, H. (1931). The problem of soil erosion in the United States. *Ann. Assoc. Am. Geogr.* **21,** 147–170.

[85] Blevins, R. L., Midkiff, D. V., and Frye, W. W. (1987). Interior low plateaus. *In* "Soil Erosion and Productivity" (J. W. Gilliam and G. D. Bubenzer, Eds.), pp. 44–52. Southern Cooperative Series Bulletin 360. Wisconsin Agric. Exp. Stn., Madison, WI.

Boardman, J. (1998). An average soil erosion rate for Europe: Myth or reality? *J. Soil Water Cons.* **53**(1), 46–50.

Bojö, J. (1996). The costs of land degradation in Sub-Saharan Africa. *Ecol. Econ.* **16,** 161–173.

Brady, N. C., and Weil, R. R. (1999). "The Nature and Properties of Soils," 12th ed. Prentice-Hall, Upper Saddle River, NJ.

[7]Bramble-Brodahl, M., Fosberg, M. A., Walker, D. J., and Falen, A. L. (1985). Changes in soil productivity related to changing topsoil. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 18–27. American Society of Agricultural Engineers, St. Joseph, MI.

Brown, L. R. (1994). Facing food insecurity. *In* "State of the World 1994" (L. R. Brown, A. Durning, C. Flavin, H. French, N. Lenssen, M. Lowe, A. Misch, S. Postel, M. Renner, L. Starke, P. Weber, and Y. Young, Eds.), pp. 177–197. Norton, New York.

Brown, L. R., and Wolf, E. C. (1984a). "Soil Erosion: Quiet Crisis in the World Economy," Worldwatch Paper No. 60. Worldwatch Institute, Washington, DC.

Brown, L. R., and Wolf, E. C. (1984b). Getting back on track. *In* "State of the World 1985" (L. R. Brown, W. U. Chandler, C. Flavin, C. Pollock, S. Postel, L. Starke, and E. C. Wolf, Eds.), pp. 222–246. Norton, New York.

Bruce, R. R., Wilkinson, S. R., and Langdale, G. W. (1987). Legume effects on soil erosion and productivity. *In* "The Role of Legumes in Conservation Tillage Systems" (J. F. Power, Ed.), pp. 127–138. Soil Conservation Society of America, Akeny, IA.

[8]Bruce, R. R., Langdale, G. W., West, L. T., and Miller, W. P. (1995). Surface soil degradation and soil productivity restoration and maintenance. *Soil Sci. Soc. Am. J.* **59,** 654–660.

Burnett, E., Stewart, B. A., and Black, A. L. (1985). Regional effects of soil erosion on crop productivity-Great Plains. *In* "Soil Erosion and Crop Productivity" (R. F. Follett and B. A. Stewart, Eds.), pp. 285–304. ASA-CSSA-SSSA, Madison, WI.

Butell, R., and Naive, J. J. (1978). Factors affecting corn yields. "Feed Situation," pp. 14–16. Economics, Statistics, and Cooperatives Service, U.S. Department of Agriculture, Washington, DC.

Cann, M., Dumanski, J., and Brklacich, M. (1992). "The Impacts of Soil Degradation on Crop Yields in the Canadian Prairies: An Annotated Bibliography." Centre for Land and Biological Resources Research, Research Branch, Agriculture Canada, Ottawa, ON.

[9]Carlson, C. W., Grunes, D. L., Alessi, J., and Reichman, G. A. (1961). Corn growth on Gardena surface and subsoil as affected by applications of fertilizer and manure. *Soil Sci. Soc. Am. Proc.* **25,** 44–47.

[10]Carter, D. L., Berg, R. D., and Sanders, B. J. (1985). The effect of furrow irrigation erosion on crop productivity. *Soil Sci. Soc. Am. J.* **49,** 207–211.

[11]Chengere, A., and Lal, R. (1995). Soil degradation by erosion of a Typic Hapludalf in central Ohio and its rehabilitation. *Land Degrad. Rehab.* **6**(4), 223–238.

Clarke, A. L. (1986). Cultivation. *In* "Australian Soils: The Human Impact" (J. F. Isbell and J. S. Russell, Eds.), pp. 273–303. Univ. of Queensland Press, St. Lucia.

Cleveland, C. J. (1995). Resource degradation, technical change, and the productivity of energy use in U.S. agriculture. *Ecol. Econ.* **13,** 185–201.

Crosson, P. R. (1986). Soil erosion and policy issues. *In* "Agriculture and the Environment" (T. Phipps, P. Crosson, and K. Price, Eds.), pp. 35–73. Resources for the Future, Washington, DC.

Crosson, P. R. (1997). The on-farm economic costs of soil erosion. *In* "Methods for Assessment of Soil Degradation" (R. Lal, W. H. Blum, C. Valentin, and B. A. Stewart, Eds.), pp. 495–511. CRC Press, Boca Raton, FL.

Crosson, P. R., and Stout, A. T. (1983). "Productivity Effects of Cropland Erosion in the United States." Resources for the Future, Washington, DC.

Daniels, R. B., Gilliam, J. W., Cassel, D. K., and Nelson, L. A. (1985). Soil erosion class and landscape position in the North Carolina Piedmont. *Soil Sci. Soc. Am. J.* **49,** 991–995.

Daniels, R. B., Gilliam, J. W., Cassel, D. K., and Nelson, L. A. (1987). Quantifying the effects of past soil erosion on present soil productivity. *J. Soil Water Cons.* **42**(3), 183–187.

Davis, D. S., and Browne, S. (1996). T12.9 Soil and resources. *In* "Natural History of Nova Scotia," Vol. 1, pp. 355–359. Nova Scotia Museum of Natural History, Halifax.

[12]DeHaan, K. R., Vessey, G. T., Holmstrom, D. A., McLeod, J. A., Sanderson, J. B., and Carter, M. R. (1999). Relating potatoe yield to the level of soil degradation using a bulk yield monitor and differential global positioning systems. *Compu. Electr. Agric.* **23,** 133–143.

den Biggelaar, C. (1994). "Farmer Knowledge and Experimentation with Trees and Tree Cultivation in Agroforestry Systems in Rwanda". Ph.D. dissertation, Department of Forestry, Michigan State University, East Lansing, MI.

den Biggelaar, C., and Suvedi, M. (1998). "An Evaluation of the North Central Region SARE Producer Grant Program". AEE Center for Evaluative Studies, Michigan State University, East Lansing, MI.

[13]Dormaar, J. F., and Lindwall, C. W. (1984). Restoring productivity to an eroded dark brown chernozemic soil under dryland conditions. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 182–192. American Society of Agricultural Engineers, St. Joseph, MI.

[14]Dormaar, J. F., Lindwall, C. W., and Kozub, G. C. (1986). Restoring productivity to an artificially eroded dark brown chernozemic soil under dryland conditions. *Can. J. Soil Sci.* **66,** 273–285.

[15]Dormaar, J. F., Lindwall, C. W., and Kozub, G. C. (1988). Effectiveness of manure and commercial fertilizer in restoring productivity of an artificially eroded dark brown chernozemic soil under dryland conditions. *Can. J. Soil Sci.* **68,** 669–679.

Dregne, H. E. (1995). Erosion and soil productivity in Australia and New Zealand. *Land Degrad. Rehab.* **6,** 71–78.

Dumanski, J., Gregorich, L. J., Kirkwood, V., Cann, M. A., Culley, J. L. B., and Coote, D. R. (1994). "Status of Land Management Practices on Agricultural Land in Canada," Technical Bulletin 1994-3E. Center for Land and Biological Resources Research, Agriculture and Agri-Food Canada, Ottawa, ON.

Dumanski, J., Coote, D., Lucerek, G., and Lok, C. (1986). Soil conservation in Canada. *J. Soil Water Cons.* **41,** 204–210.

[16]Ebeid, M. M., Lal, R., Hall, G. F., and Miller, F. (1995). Erosion effects on soil properties and soybean yield of a Miamian soil in western Ohio in a season with below normal rainfall. *Soil Technol.* **8**(2), 97–108.

[17]Eck, H. V. (1968). Effect of topsoil removal on nitrogen supplying ability of Pullman silty clay loam. *Soil Sci. Soc. Proc.* **32,** 686–691.

[83]Eck, H. V. (1987). Characteristics of exposed subsoil—At exposure and 23 years later. *Agron. J.* **79,** 1067–1073.

[84]Eck, H. V., Hauser, V. L., and Ford, R. H. (1965). Fertilizer needs for restoring productivity on Pullman silty clay loam after various degrees of soil removal. *Soil Sci. Soc. Am. Proc.* **29,** 209–213.

Economic Research Service (ERS), Natural Resources and Environment Division (1997). Land and soil quality. *In* "Agricultural Resources and Environmental Indicators 1996–97," pp. 41–49. USDA Economic Research Service, Washington, DC.

Ehrlich, P. R., and Ehrlich, A. H. (1991). "Healing the Planet." Addison-Wesley, Reading, UK.

[18]Fahnestock, P., Lal, R., and Hall, G. F. (1995). Land use and erosional effects on two Ohio Alfisols II: Crop yields. *J. Sust. Agric.* **7**(2/3), 85–100.

Fairbairn, G. L. (1984). "Will the Bounty End? The Uncertain Future of Canada's Food Supply." Western Producer Prairie Books, Saskatoon, SK.

[19]Fenton, T. E., Duncan, E. R., Shrader, W. D., and Dumenil, L. C. (1971). "Productivity Levels of Some Iowa Soils." Special Report No. 66. Iowa Agric. Exp. Stn., Ames, IA (23 pp.).

Follett, R. F., and Stewart, B. A. (Eds.) (1985). "Soil Erosion and Crop Productivity." ASA-CSSA-SSSA, Madison, WI.

Frye, W. W. (1987). The effects of soil eorsion on crop productivity. *In* "Agricultural Soil Loss: Processes, Policies and Prospects" (J. M. Harlin and G. M. Berardi, Eds.), pp. 151–171. Westview Special Studies in Agriculture Science and Policy, Boulder, CO.

[20]Frye, W. W., Murdock, L. W., and Blevins, R. L. (1983). Corn yield–fragipan depth relations on a Zanesville soil. *Soil Sci. Soc. Am. J.* **47,** 1043–1045.

[21]Frye, W. W., Ebelhar, S. A., Murdock, L. W., and Blevins, R. L. (1982). Soil erosion effects on properties and productivity of two Kentucky soils. *Soils Sci. Soc. Am. J.* **46,** 1051–1055.

[22]Frymire, W. L. (1980). "Topsoil Depth (Mollic Epipedon) and its Effect on Crop Productivity in Latah County, Idaho." M.S. thesis, Department of Soil Science, University of Idaho, Moscow, Idaho.

Furtan, W. H., and Hosseini, S. S. (1999). "Economic and Institutional Considerations for Soil Depletion," CSALE Occasional Paper 1. Univ. of Saskatchewan, Center for Studies in Agriculture, Law and Environment, Saskatoon.

[23]Gantzer, C. J., and McCarthy, T. R. (1985). Corn yield prediction for a claypan soil using a productivity index. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 170–181. American Society of Agricultural Engineers, St. Joseph, MI.

Geisler, M., and den Biggelaar, C. (1998). "Michigan Groundwater Stewardship Program." Report of the groundwater stewardship practices case studies on abandoned well closure, equipment calibration and pre-side dress nitrogen testing. AEE Center for Evaluative Studies, Michigan State University, East Lansing, MI.

[86]Gilliam, J. W., Langdale, G. W., and Bruce, R. R. (1987). Southern Piedmont. *In* "Soil Erosion and Productivity" (J. W. Gilliam and G. D. Bubenzer, Eds.), pp. 24–35. Southern Cooperative Series Bulletin 360. Wisc. Agric. Exp. Stn., Madison, WI.

[24]Gollany, H. T., Schumacher, T. E., Lindstrom, M. J., Evenson, P. D., and Lemme, G. D. (1992). Topsoil depth and desurfacing effects on properties and productivity of a Typic Argiustoll. *Soil Sci. Soc. Am. J.* **56,** 220–225.

[25]Greb, B. W., and Smika, D. E. (1985). Topsoil removal effects on soil chemical and physical properties. *In* "Soil Erosion and Conservation" (S. A. El-Swaify, W. C. Moldenhauer, and A. Lo, Eds.), pp. 316–327. Soil Conservation Society of America, Ankeny, IA.

[26]Hairston, J. E., Sanford, J. O., Rhoton, F. E., Miller, J. G., and Gill, K. B. (1989). "Effects of Soil Depth, Organic Matter and Rainfall on Soybean Yield in the Mississippi Blackland Prairie." Mississippi Agric. For. Exp. Stn. Tech. Bul. 163, Mississipi State, MS (7 pp.).

[87]Hajek, B. F., and Collins, M. E. (1987). Results of experiments conducted on various land resource areas. Coastal Plain and Tennessee Valley regions. *In* "Soil Erosion and Productivity" (J. W.

Gilliam and G. D. Bubenzer, Eds.), pp. 2–23. Southern Cooperative Series Bull. 360. Wisc. Agric. Exp. Stn., Madison, WI.

Haji, H. M., and Hunt, L. A. (1999). Genotype $\times$ environment interactions and underlying environmental factors for winter wheat in Ontario. *Can. J. Plant Sci.* **79,** 497–505.

Halvorson, M. A. (1999). "LTER Agronomic Grain Yield and GIS Yield Monitoring: Extension Summary for the 1999 All-Investigator Meeting. W. K. Kellogg Biological Station, Gull Lake, MI. Internet URL: http://lter.kbs.msu.edu/Meetings/Extension_summary/Halvorson2.htm.

Harris, C., and Warkentin, J. (1974). "Canada Before Confederation: A Study in Historical Geography." Oxford Univ. Press, Oxford.

Heimlich, R. E. (1989). "Productivity and Erodibility of US Cropland." Report No. 604. USDA Economic Research Service, Washington, DC.

[27]Henning, S. J., and Khalaf, J. A. (1985). Topsoil depth and management effects on crop productivity in north central Iowa. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 59–65. American Society of Agricultural Engineers, St. Joseph, MI.

[28]Hepler, P. R., Long, L. H., and Ferwerda, J. A. (1983). "Field Appraisal of Resource Management Systems "Farms": Crop Yield and Quality Relationships with Soil Erosion—1980." Maine Agric. Exp. Stn. Bull. No. 799, Orono, ME (30 pp.).

Hoag, D. L. (1998). The intertemporal impact of soil erosion on non-uniform soil profiles: A new direction in analyzing erosion impacts. *Agric. Sys.* **56**(4), 415–429.

[29]Horner, G. M. (1960). Effect of cropping systems on runoff, erosion and wheat yields. *Agron. J.* **52**(6), 342–344.

International Institute for Sustainable Development (IISD) (1999). Degradation of prairie soil resources. Internet URL: http://iisd1.iisd.ca/agri/GPsoil.htm.

[30]Ives, R. M., and Shaykewich, C. F. (1987). Effect of simulated soil erosion on wheat yields on the humid Canadian prairie. *Can. J. Soil Sci.* **42**(3), 205–208.

[31]Izaurralde, R. C., Solberg, E. D., Nyborg, M., and Malhi, S. S. (1998). Immediate effects of topsoil removal on crop productivity loss and its restoration with commercial fertilizers. *Soil Tillage Res.* **46**(3/4), 251–259.

Johnson, D. L., and Lewis, L. A. (1995). "Land Degradation: Creation and Destruction." Blackwell, Cambridge, MA.

Johnston, A. E., Barraclough, P. B., Poulton, P. R., and Cawson, C. J. (1998). "Assessment of Some Spatially Variable Soil Factors Limiting Crop Yields." Proceedings No. 419, paper presented to the International Fertilizer Society at a Conference in Cambridge, UK, 10 December 1998. The International Fertilizer Society, York, UK.

Kaiser, V. (1967). Soil erosion and wheat yields in Whitman County, Washington. *Northwest Sci.* **41**(2), 86–91.

Karlen, D. L., Sadler, E. J., and Busscher, W. J. (1990). Crop yield variation associated with Coastal Plain soil map units. *Soil Sci. Soc. Am. J.* **54,** 859–865.

Kraus, H. A., and Allmaras, R. R. (1982). Technology masks the effect of soil erosion on wheat yields: A case study in Whitman County, Washington. *In* "Determinants of Soil Loss Tolerance" (B. L. Schmidt, R. R. Allmaras, J. V. Mannering, and R. J. Papendick, Eds.), pp. 75–86. ASA Special Publication No. 45. American Society of Agronomy, Madison, WI.

Lal, R. (1988). Monitoring soil erosion's impact on crop productivity. *In* "Soil Erosion Research Methods" (R. Lal, Ed.), pp. 187–200. Soil and Water Conservation Society, Ankeny, IA.

Lal, R. (1987). Effects of erosion on crop productivity. *Crit. Rev. Plant Sci.* **5**(4), 303–364.

Lal, R. (1997). Agronomic impact of soil degradation. *In* "Methods for Assessment of Soil Degradation" (R. Lal, W. H. Blum, C. Valentine, and B. A. Stewart, Eds.), pp. 459–474. Boca CRC Press, Boca Raton, FL.

Lal, R. (1998). Soil erosion impact on agronomic productivity and environment quality. *Crit. Rev. Plant Sci.* **17**(4), 319–464.

Lal, R., and Stewart, B. A. (1990). "Soil Degradation: Advances in Soil Science 11." Springer-Verlag, New York.

Lal, R., and Stewart, B. A. (Eds.) (1995). "Soil Management: Experimental Basis for Sustainability and Environmental Quality." CRC Press, Boca Raton, FL.

Lamb, J. A., Dowdy, R. H., and Anderson, J. L. (1995). Grain yield and N uptake variability across a sandy landscape. *In* "Clean Water—Clean Environment—21st Century, Volume II: Nutrients; Proceedings of Team Agriculture—Working to Protect Water Resources, Kansas City, MO, March 5–8 1995," pp. 115–118. American Society of Agricultural Engineers, St. Joseph, MI.

Lamb, J. A., Dowdy, R. H., Anderson, J. L., and Rehm, G. W. (1997). Spatial and temporal stability of corn grain yields. *J. Prod. Agric.* **10**(3), 410–414.

[32]Lamb, J., Andrews, J. S., and Gustafson, A. F. (1944). "Experiments in the Control of Soil Erosion in Southern New York." Cornell Agric. Exp. Stn. Bull. 811, Ithaca, NY.

Langdale, G. W., and Shrader, W. D. (1982). Soil erosion effects on soil productivity of cultivated cropland. *In* "Determinants of Soil Loss Tolerance" (B. L. Schmidt, R. R. Allmaras, J. V. Mannering, and R. J. Papendick, Eds.), pp. 41–55. ASA Special Publication No. 45. American Society of Agronomy, Madison, WI.

[88]Langdale, G. W., Bruce, R. R., and Thomas, A. W. (1987). Restoration of eroded Southern Piedmont land in conservation tillage systems. *In* "The Role of Legumes in Conservation Tillage Systems: Proc. Nat. Conf., Univ. of Georgia, Athens, April 27–29, 1987" (J. F. Power, ed.), pp. 142–143. Soil Conservation Society of America, Ankeny, IA.

[33]Langdale, G. W., Box, J. E., Leonard, R. A., Barnett, A. P., and Fleming, W. G. (1979). Corn yield reduction on eroded southern Piedmont soils. *J. Soil Water Cons.* **34**(5), 226–228.

[34]Larney, F. J., and Janzen, H. H. (1997). A simulated erosion approach to assess rates of cattle manure and phosphorus fertilizer for restoring productivity to eroded soils. *Agric. Ecosys. Environ.* **65,** 113–126.

[35]Larney, F. J., Janzen, H. H., and Olson, B. M. (1995). Efficacy of inorganic fertilizers in restoring wheat yields on artificially eroded soils. *Can. J. Soil Sci.* **75,** 369–377.

[36]Larney, F. J., Janzen, H. H., Olson, B. M., and Lindwall, C. W. (1991). The impact of simulated erosion on soil productivity and methods for its amendment. *In* "Proc., 28th Annual Alberta Soil Science Workshop, February 19–21, 1991, Lethbridge, AB," pp. 277–285. Faculty of Extension, University of Alberta, Edmonton, AB, Canada.

[37]Larney, F. J., Bullock, M. S., Janzen, H. H., Ellert, B. H., and Olson, E. C. S. (1998). Wind erosion effects on nutrient redistribution and soil productivity. *J. Soil Water Cons.* **53**(2), 133–140.

[38]Larney, F. J., Izaurralde, R. C., Janzen, H. H., Olson, B. M., Solberg, E. D., Lindwall, C. W., and Nyborg, M. (1995). Soil erosion-crop productivity relationships for six Alberta soils. *J. Soil Water Cons.* **50**(1), 87–91.

Larson, W. E., Pierce, F. J., and Dowdy, R. H. (1983a). Soil erosion and productivity: A rational look at a complex situation. *Crops Soils Mag.* **35**(9), 19–20.

Larson, W. E., Pierce, F. J., and Dowdy, R. H. (1983b). The threat of soil-erosion to long-term crop production. *Science* **219,** 458–465.

Larson, W. E., Fenton, T. E., Skidmore, E. L., and Benbrook, C. M. (1985). Effects of soil erosion on soil properties as related to crop productivity and classification. *In* "Soil Erosion and Crop Productivity" (R. F. Follett and B. A. Stewart, Eds.), pp. 189–211. ASA-CSSA-SSSA, Madison, WI.

Larson, W. E., Foster, G. R., Allmaras, R. R., and Smith, C. M. (Eds.) (1990). "Proceedings of the Soil Erosion/Productivity Workshop." University of Minnesota, St. Paul, MN.

[39]Latham, E. E. (1940). Relative productivity of the A horizon of Cecil sandy loam and the B and C horizons exposed by erosion. *J. Am. Soc. Agron.* **32**(12), 950–954.

Lindert, P. H. (1999). The bad earth? China's soils and agricultural development since the 1930s. *Econ. Dev. Cult. Change* **47**(4), 701–736.

[40]Lindstrom, M. J., Schumacher, T. E., Lemme, G. D., and Gollany, H. M. (1986). Soil characteristics of a mollisol and corn (*Zea mays* L.) growth 20 years after topsoil removal. *Soil Tillage Res.* **7,** 51–62.

[41]Lindstrom, M. J., Schumacher, T. E., Lemme, G. D., Swan, J. P., and Nelson, W. W. (1987). Erosion–productivity influence on three northwestern corn belt mollisols. *In* "Proceedings of the 1987 International Winter Meetings of the American Society of Agricultural Engineers, December 15–18, 1987, Chicago, IL." Paper no. 87-2599. American Society of Agricultural Engineers, St. Joseph, MI.

Littleboy, M., Cogle, A. L., Smith, G. D., Rao, K. P. C., and Yule, D. F. (1996). Soil management and production of Alfisols ion the semi-arid tropics IV: Simulation of decline in productivity caused by soil erosion. *Aust. J. Soil Res.* **34,** 127–138.

Loch, R. J., and Silburn, D. M. (1997). Soil erosion. *In* "Sustainable Crop Production in the Subtropics: An Australian Perspective" (A. L. Clarke and P. B. Wylie, Eds.). pp. 27–63. Department of Primary Industries, Brisbane, Qld.

[42]Lowery, B., Andraski, B. J., and Paulson, W. H. (1990). "Best Management Practices for an Eroded Soil: Transactions of the 14th International Congress of Soil Science, Kyoto, Japan, August 12–18, 1990," Vol. VII, pp. 380–381. International Society of Soil Science, Kyoto, Japan.

Maetzold, J., and Alt, K. (1986). "Forum on Erosion Productivity Impact Estimators: Assessment and Planning Report." Soil Conservation Service, Appraisal and Program Development Division, Washington, DC.

Magleby, R., Sandretto, C., Crosswhite, W., and Osborn, C. T. (1995). "Soil Erosion and Conservation in the United States: An Overview." Agric. Info. Bull. 718. USDA Economic Research Service, Washington, DC.

Mannering, J. V., Franzmeier, D. P., Schertz, D. L., Moldenhauer, W. C., and Norton, L. D. (1985). Regional effects of soil erosion on crop productivity—Midwest. *In* "Soil Erosion and Crop Productivity" (R. F. Follett and B. A. Stewart, Eds.), pp. 271–284. ASA-CSSA-SSSA, Madison, WI.

[44]Massee, T. W. (1990). Simulated erosion and fertilizer effects on winter wheat cropping intermountain dryland area. *Soil Sci. Soc. Am. J.* **54,** 1720–1725.

[43]Massee, T. W., and Waggoner, H. O. (1985). Productivity losses from soil erosion on dry cropland in the intermountain region. *J. Soil Water Cons.* **40,** 447–450.

[45]McDaniel, T. A., and Hajek, B. F. (1985). Soil erosion effects on crop productivity and soil properties in Alabama. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 48–58. American Society of Agricultural Engineers, St. Joseph, MI.

[46]Mielke, L. N., and Schepers, J. S. (1986). Plant response to topsoil thickness on an eroded loess soil. *J. Soil Water Cons.* **41,** 59–63.

[82]Miller, C. F. (1985). "Effects of Erosion on the Productivity of Two Ustolls." M.S. thesis, Department of Agronomy, South Dakota State Univ., Brookings, SD.

Miller, J. G., McConnaughy, P. K., and Hairston, J. E. (1985). Erosion-productivity relationships for Blackland prairie soils in Mississippi. *In* "Proceedings of the 1985 Southern Region No-till Conference, July 16–17, 1985, Griffin, Georgia" (W. L. Hargrove, F. C. Boswell, and G. W. Langdale, Eds.), pp. 159–162. Agric. Exp. Stn., University of Georgia, Athens, GA.

Miller, M. H. (1986). Soil degradation in eastern Canada: Its extent and impact. *Can. J. Agric. Econ.* **33,** 7–18.

Miller, M. P., Singer, M. J., and Nielsen, D. R. (1988). Spatial variability of wheat yield and soil properties on complex hills. *Soil Sci. Soc. Am. J.* **52,** 1133–1141.

[47]Mokma, D. L., and Sietz, M. A. (1992). Effects of soil erosion on corn yields on Marlette soils in south-central Michigan. *J. Soil Water Cons.* **47**(4), 325–327.

[48]Monreal, C. M., Zentner, R. P., and Robertson, J. A. (1995). The influence of management on soil loss and yield of wheat in chernozemic and luvisolic soils. *Can. J. Soil Sci.* **75,** 567–574.

[49]Murray, W. G., Englehorn, A. J., and Griffin, R. A. (1939). "Yield Tests and Land Valuation, pp. 54–76." Iowa Agric. Exp. Stn. Res. Bull. 252, Ames, IA.

[50]Musgrave, R. n.d. Unpublished data, Cornell University, Ithaca, NY. *In* "Soil Erosion and Crop Productivity" (R. F. Follett and B. A. Stewart, Eds.), p. 243. ASA-CSSA-SSSA, Madison, WI.

National Agricultural Lands Study. (1981). "Soil Degradation: Effects on Agricultural Productivity." Interim Report No. 4. Government Printing Office, Washington, DC.

National Agricultural Statistics Service (NASS). (1999). "1997 Census of Agriculture." USDA National Agricultural Statistics Service, Washington, DC.

National Soil Erosion-Soil Productivity Research Planning Committee (NSE-SPRPC). (1981). Soil erosion effects on soil productivity: A research perspective. *J. Soil Water Cons.* **36**(2), 82–90.

Natural Resources Canada (1995). Geographical names of Canada. Internet URL: http://geonames.nrcan.gc.ca/english/cgndb.html.

Natural Resources Conservation Service (NRCS). (1999). "Summary Report, 1997 National Resources Inventory." USDA Natural Resources Conservation Service, Washington, DC. Internet URL: http://www.nhq.nrcs.usda.gov/NRI/1997/summary_report/.

Nowak, P. J., Timmons, J., Carlson, J., and Miles, R. (1985). Economic and social perspectives on T-values relative to soil erosion and crop productivity. *In* "Soil Erosion and Crop Productivity" (R. F. Follett and B. A. Stewart, Eds.), pp. 119–132. ASA-CSSA-SSSA, Madison, WI.

[51]Odell, R. T. (1950). Measurement of the productivity of soils under various environmental conditions. *Agron. J.* **42,** 282–292.

Office of Technology Assessment (OTA). (1982). Land productivity problems. *In* "Impacts of Technology on U.S. Cropland and Rangeland Productivity" (OTA), pp. 23–63. Government Printing Office, Washington, DC.

Oldeman, R., Hakkeling, R., and Sombroeck, W. (1990). "World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note." International Soil Reference and Information Center, Wageningen Na United Nations Environment Progamme, Nairobi, Kenya.

[53]Olson, K. R., and Carmer, S. G. (1990). Corn yield and plant population differences between eroded phases of Illinois soils. *J. Soil Water Cons.* **45**(5), 562–566.

[52]Olson, K. R., and Nizeyimana, E. (1988). Maize yield response differences between moderately and severely eroded Illinois soils. *Soil Surv. Horiz.* **29**(2), 57–62.

Olson, K. R., Lal, R., and Norton, L. D. 1994. Evaluation of methods to study soil erosion–productivity relationships. *J. Soil Water Cons.* **49**(6), 586–590.

[54]Olson, K. R., Mokma, D. L., Lal, R., Schumacher, T. E., and Lindstrom, M. J. (1999). Erosion impacts on crop yield for selected soils of the North Central United States. *In* "Soil Quality and Soil Erosion" (R. Lal, Ed.), pp 259–284. CRC Press, Boca Raton, FL.

[55]Olson, T. C. (1977). Restoring the productivity of a glacial till soil after topsoil removal. *J. Soil Water Cons.* **32,** 130–132.

Perrens, S. J., and Trustum, N. A. (1984). "Assessment and Evaluation of Soil Conservation Policy." Report, Workshop on Policies for Soil and Water Conservation, 25–27 January 1983, East West Center, Honolulu, Hawaii.

[56]Pettry, D. E., Wood, C. W., Jr., and Soileau, J. M. (1985). Effect of topsoil thickness and horizontation of a virgin coastal plain soil on soybean yields. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 66–74. American Society of Agricultural Engineers, St. Joseph, MI.

Pierce, F. J. (1991). Erosion productivity impact prediction. *In* "Soil Management for Sustainability" (R. Lal and F. J. Pierce, Eds.), pp. 35–52. Soil and Water Conservation Society, Ankeny, IA.

Pimentel, D. (ed.) (1993). "World Soil Erosion and Conservation." Cambridge Univ. Press, Cambridge, UK.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., and Blair, R. (1995). Environmental and economic costs of soil erosion and conservation benefits. *Science* **267,** 1117–1123.

Pimentel, D., Terhune, E. C., Dyson-Hudson, R., Rochereau, S., Samis, R., Smith, E. A., Denman, D., Reitschneider, D., and Shepard, M. (1976). Land degradation: Effects on food and energy resources. *Science* **194,** 149–155.

Ponzi, D. (1993). "Soil Erosion and Productivity: A Brief Review." *Desertification Control Bulletin* No. 22, pp. 36–44.

[57]Power, J. F., Sandoval, F. M., Ries, R. E., and Merrill, S. D. (1981). Effects of topsoil and subsoil thickness on soil water content and crop production on a disturbed soil. *Soil Sci. Soc. Am. J.* **45,** 124–129.

Prairie Farm Rehabilitation Agency (PFRA) (1983). "Land Degradation and Soil Conservation Issues on the Canadian Prairies." Soil and Water Conservation Branch, PFRA, Regina.

[58]Rasmussen, P. E., and Rohde, C. R. (1991). Tillage, soil depth and precipitation effects on wheat response to nitrogen. *Soil Sci. Soc. Am. J.* **55**(1), 121–124.

Renard, K. G., and Follett, R. F. (1985). A research strategy for assessing the effect of erosion on future soil productivity in the United States. *In* "Soil Erosion and Conservation" (S. A. El-Swaify, W. C. Moldenhauer, and A. Lo, Eds.), pp. 691–702. Soil Conservation Society of America, Ankeny, IA.

[59]Rhoton, F. E. (1990). Soybean yield response to various depths of erosion on a fragipan soil. *Soil Sci. Soc. Am. J.* **54,** 1073–1079.

Ribaudo, M. (1989). "Water Quality Benefits from the Conservation Reserve Program." AER 606, USDA Economic Research Service, Washington, DC.

Rijsberman, F. R., and Wolman, M. G. (Eds.) (1984). "Quantification of the Effect of Erosion on Soil Productivity in an International Context." Delft Hydraulics Laboratory, Delft, The Netherlands.

[89]Salchow, E., and Lal, R. (1999). Crop yield variability due to erosion on a complex landscape in west central Ohio. *In* "Integrated Watershed Management in the Global Ecosystem" (R. Lal, Ed.), pp. 195–207. CRC Press, Boca Raton, FL.

[60]Schertz, D. L., Moldenuer, W. C., Livingston, S. J., Weesies, G. A., and Hintz, E. A. (1989). Effect of past soil erosion on crop productivity in Indiana. *J. Soil Water Cons.* **44,** 604–608.

[61]Schertz, D. L., Moldenhauer, W. C., Franzmeier, D. P., and Sinclair, H. R., Jr. (1985). Field evaluation of the effect of soil erosion on crop productivity. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 9–17. American Society of Agricultural Engineers, St. Joseph, MI.

[62]Schumacher, T. E., Lindstrom, M. J., Mokma, D. L., and Nelson, W. W. (1994). Corn yield: Erosion relationships of representative loess and till soils in the North Central United States. *J. Soil Water Cons.* **49**(1), 77–81.

Shaffer, M. J. (1985). Simulation model for soil erosion–productivity relationships. *J. Environ. Qual.* **14,** 144–150.

[63]Shaffer, M. J., Schumacher, T. E., and Ego, C. L. (1994). Long-term effects of erosion and climate interactions on corn yield. *J. Soil Water Cons.* **49**(3), 272–275.

Simmonds, N. W. (1979). "Principles of Crop Improvement." Longman, London.

[64]Smith, D. D. (1946). The effect of contour planting on crop yield and erosion losses in Missouri. *J. Am. Soc. Agron.* **38**(9), 811–819.

Soil Survey Staff (1999). "Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys," USDA-NRCS Agricultural Handbook No. 436, 2nd ed. USDA Natural Resources Conservation Service, Washington, DC.

Sparrow, H. O. (1984). "Soil at Risk: Canada's Eroding Future." The Standing Senate Committee on Agriculture, Fisheries and Forestry, Senate of Canada, Ottawa.

Spomer, R. G., and Piest, R. F. (1982). Soil productivity and erosion of Iowa loess soils. *Trans. ASAE* **25,** 1295–1299.

[65]Stallings, J. H. (1957). Erosion and Productivity. *In* "Soil Conservation," pp. 195–220. Prentice-Hall, Englewood Cliffs, NJ.

Statistics Canada (1997). "Agricultural Profile of Canada." Statistics Canada, Division of Agriculture, Ottawa.

Stocking, M. (1984). "Erosion and Soil Productivity: A Review." Food and Agriculture Organization, Soil Conservation Programme, Land and Water Development Division, Rome, Italy.

Stocking, M. (1994). Soil erosion and conservation: A place for soil science? *In* "Soil Science and Sustainable Land Management in the Tropics" (J. K. Syers and D. L. Rimmer, Eds.), pp. 40–58. CAB International, Wallingford, UK.

Stocking, M., and Peake, L. (1985). "Erosion-induced Loss in Soil Productivity: Trends in Research and International Cooperation." Food and Agriculture Organization, Rome, Italy.

Stocking, M. A., and Sanders, D. W. (1993). The impact of erosion on soil productivity. *Contour-Jakarta* **5**(1), 12–16.

[66]Stone, J. R., Gilliam, J. W., Cassel, D. K., Daniels, R. B., Nelson, L. A., and Kleiss, H. J. (1985). Effect of erosion and landscape position on the productivity of Piedmont soils. *Soil Sci. Soc. Am. J.* **49,** 987–991.

[67]Swan, J. B., Shaffer, M. J., Paulson, W. H., and Peterson, A. E. (1987). Simulating the effects of soil depth and climatic factors on corn yield. *Soil Sci. Soc. Am. J.* **51,** 1025–1032.

[69]Tanaka, D. L. (1995). Spring wheat straw production and composition as influenced by topsoil removal. *Soil Sci. Soc. Am. J.* **59**(3), 649–654.

[68]Tanaka, D. L., and Aase, J. K. (1989). Influence of topsoil removal and fertilizer application on spring wheat yields. *Soil Sci. Soc. Am. J.* **53,** 228–232.

Tengberg, A., and Stocking, M. (1997). "Erosion-Induced Loss in Soil Productivity and Its Impacts on Agricultural Production and Food Security." Paper presented at the FAO/AGRITEX Expert Consultation on Integrated Soil Management for Sustainable Agriculture and Food Security in Southern and Eastern Africa, Harare, Zimbabwe, 8–12 December 1997.

Terry, R. (1997). Aghrt 282 class lectures: Soil erosion. Internet URL: http://ucs.byu.edu/bioag/aghort/282pres/erosion/.

[81]Thomas, H. L., Stephenson, R. E., Freese, C. R., Chapin, R. W., and Huggins, W. W. (1943). The economic effect of soil erosion on wheat yields in Eastern Oregon. *Oregon Ag. Exp. Stn. Circular* 157, Corvallis, OR (32 pp.).

[71]Thompson, A. L., Gantzer, C. J., and Anderson, S. H. (1991). Topsoil depth, fertility, water management and weather influences on Yield. *Soil Sci. Soc. Am. J.* **55**(4), 1085–1091.

[70]Thompson, A. L., Gantzer, C. J., and Hammer, R. D. (1992). Productivity of a claypan soil under rain-fed and irrigated conditions. *J. Soil Water Cons.* **47**(5), 405–410.

[72]Thompson, P. J., Simpson, T. W., and Baker, J. C. (1991). Topsoil depth, fertility, water management, and weather influences on yield. *Soil Sci. Soc. Am. J.* **55,** 1085–1091.

Timlin, D. J., Pachepsky, Y., Snyder, V. A., and Bryant, R. B. (1998). Spatial and temporal variability of corn yield on a hillslope. *Soil Sci. Soc. Am. J.* **62,** 764–773.

Tomlin, A. D., and Umphrey, G. J. (1996). Productivity of agricultural soils. Internet URL: http://www.cciw.ca/eman-temp/reports/publications/tomlin/intro.html.

[90]Tyler, D. D., Graveel, J. G., and Jones, J. R. (1987). Southern loess belt. *In* "Soil Erosion and Productivity" (J. W. Gilliam and G. D. Bubenzer, Eds.), pp. 36–43. Southern Cooperative Series Bull. 360. Wisconsin Agric. Exp. Stn., Madison, WI.

United States Bureau of the Census (1993). "1992 Census of Agriculture." Bureau of the Census, Washington, DC.

United States Bureau of the Census (1987). "1987 Census of Agriculture." U.S. Dept. of Commerce, Bureau of the Census, Washington, DC.

United States Department of Agriculture (USDA) (1999). "USDA Agricultural Baseline Projections to 2008." Staff Report WAOB-99-1. USDA World Agricultural Outlook Board, Office of the Chief Economist, Washington, DC.

United States Geological Survey (USGS) (2000). National Mapping Information. Geographic Names Information System, United States and Territories. Internet URL: http://mapping.usgs.gov/www/gnis/gnisform.html.

van Baren, J. H. V., and Oldeman, L. R. (1998). Human-induced soil degradation activities. *Int. Agrophys.* **12,** 37–42.

[73]Verity, G. E., and Anderson, D. W. (1990). Soil erosion effects on soil quality and yield. *Can. J. Soil Sci.* **70,** 471–484.

Vesterby, M., and Krupa, K. S. (1993). Effects of urban land conversion on agriculture. *In* "Urbanization and Development Effects on the Use of Natural Resources" (E. Thunberg and J. Reynolds, Eds.), pp. 85–114. SRDC No. 169. Southern Rural Development Center and Farm Foundation, Mississippi State, MS.

Wall, G. J., Coote, D. R., Pringle, E. A., and Shelton, I. J. (1997). "RUSLEFAC—Revised Universal Soil Loss Equation For Application in Canada." Centre for Land Biological Resources Research, Research Branch, Agriculture and Agri-Food Canada, Ottawa.

[74]Weesies, G. A., Livingston, S. J., Hosteter, W. D., and Schertz, D. L. (1994). Effect of soil erosion on crop yield in Indiana: Results of a 10 year study. *J. Soil Water Cons.* **49**(6), 597–600.

[75]Wetter, F. (1977). "The influence of topsoil depth on yield." Tech. Note 10. USDA Soil Conservation Service, Spokane, WA.

[76]White, A. W., Jr., Bruce, R. R., Thomas, A. W., Langdale, G. W., and Perkins, H. F. (1985). Characterizing productivity of eroded soils in the southern Piedmont. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 83–95. American Society of Agricultural Engineers, St. Joseph, MI.

Williams, J. R., and Tanaka, D. L. (1996). Economic evaluation of topsoil loss in spring wheat production in the northern Great Plains, USA. *Soil Tillage Res.* **37,** 95–112.

World Soil Resources Staff (1997). "Global Soil Regions Map." USDA NRCS, Soil Survey Division, World Soil Resources, Washington, DC.

[77]Wright, R. J., Boyer, D. G., Winant, W. M., and Perry, H. D. (1990). The influence of soil factors on yield differences among landscape position in an Appalachian cornfield. *Soil Sci.* **149**(6), 375–382.

[78]Xu, Z., Fausey, N. R., Lal, R., and Hall, G. F. (1997). Erosional effects on soil properties and corn (*Zea mays* L.) yield on a Miamiam soil in Ohio. *J. Sust. Agric.* **10**(4), 21–35.

[79]Yang, T., Blanchar, R. W., Hammer, R. D., and Thompson, A. L. (1996). Soybean growth and rhizosphere pH as influenced by A horizon thickness. *Soil Sci. Soc. Am. J.* **60**(6), 1901–1907.

[80]Yost, R. S., El-Swaify, S. A., Dangler, E. W., and Lo, A. K. F. (1985). The influence of simulated erosion and restorative fertilization on maize production on an oxisol. *In* "Soil Erosion and Conservation" (S. A. El-Swaify, W. C. Moldenhauer, and A. Lo, Eds.), pp. 248–261. Soil Conservation Society of America, Ankeny, IA.

Young, D. L., Taylor, D. B., and Papendick, R. I. (1985). Separating erosion and technoloy impacts on winter wheat yields in the Palouse: A statistical approach. *In* "ASAE Publication 85-8: Erosion and Soil Productivity," pp. 130–142. American Society of Agricultural Engineers, St. Joseph, MI.